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AEROPREDICTIVE METHODS FOR MISSILE ANALYSIS

by

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Various computational methods and operational computer codes used to predict and evaluate aerodynamic coefficients and flight performance of missile bodies are reviewed. Aerodynamic effects of symmetric and asymmetric flow separation are discussed, as are the differences inherent in estimating the properties of the resulting flowfields. The semi-empirical aeroprediction codes NSWC and MISSILE DATCOM are compared against experimental data for a variety of configuration geometries and flight conditions; the MISSILE DATCOM code is further used for a comparison with wind tunnel data for a Standard-type missile model. The NSWC and MISSILE DATCOM codes are found to provide accurate prediction of normal force coefficients at both low and high angle of attack, although the nonlinear effects of separated flow are only partially captured. Center of pressure coefficients are generally underpredicted, but of the correct order of magnitude. The accuracy of drag coefficient prediction is seen to diminish as missile configuration geometry becomes more complex. The NSWC program provides satisfactory prediction of pitch damping coefficients, while the MISSILE DATCOM output is inconclusive. The NSWC and MISSILE DATCOM aeroprediction codes are considered suitable for preliminary design and aerodynamic analysis. Keywords: Computer programs.

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Aeropredictive Methods for Missile Analysis

by

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ABSTRACT

Various computational methods and operational computer codes used to predict and evaluate aerodynamic coefficients and flight performance of missile bodies are reviewed. Aerodynamic effects of symmetric and asymmetric flow separation are discussed, as are the differences inherent in estimating the properties of the resulting flowfields. The semi-empirical aeroprediction codes NSWC and MISSILE DATCOM are compared against experimental data for a variety of configuration geometries and flight conditions; the MISSILE DATCOM code is further used for a comparison with wind tunnel data for a Standard-type missile model. The NSWC and MISSILE DATCOM codes are found to provide accurate prediction of normal force coefficients at both low and high angle of attack, although the nonlinear effects of separated flow are only partially captured. Center of pressure coefficients are generally underpredicted, but of the correct order of magnitude. The accuracy of drag coefficient prediction is seen to diminish as missile configuration geometry becomes more complex. The NSWC program provides satisfactory prediction of pitch damping coefficients, while the MISSILE DATCOM output is inconclusive. The NSWC and MISSILE DATCOM aeroprediction codes are considered suitable for preliminary design and aerodynamic analysis.

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I. INTRODUCTION

Flight stability and performance requirements are fundamental design considerations in tactical missile development. As missions and operational roles are redefined, so too are the aerodynamic conditions under which the missile must operate. A new flight environment may require only slight modifications to an existing system, or may involve significant design alteration and feasibility testing. The final result must, however, continue to maximize the controllability and performance of the missile, thereby maintaining a dependable and effective weapons system.

A. AERODYNAMIC MODELING

The need for design alterations can arise from new employment methods, the presence of new or upgraded threats, or an introduction of new technology. Recently the naval surface combatant community has seen the vertical launch system enter service aboard two new construction ship classes. Use of the vertical launch system for Anti-Air Warfare and Anti-Submarine Warfare places these weapons in an operational flight regime unforeseen during their development. Live-fire exercises of vertically launched weapons have been conducted, the results of which indicate that current design stability and performance require further investigation. During a test of a prototype thrust vector control (TVC) ASROC, the missile suddenly entered into an errant and unstable flight mode. Unable to control yaw plane motion, the weapon traveled a flight path nearly 90 degrees off the intended down range trajectory. Careful review of flight films and telemetry data indicates that an excessive aerodynamic yawing moment was induced through nose tip movement. Flight failure analysis suggests that this displacement in nose position most probably generated significant asymmetric vortex shedding, resulting in large out-of-plane moments, which continued even after symmetric reseating of the nose tip. [Ref. 1].

Although such asymmetric shedding of vortices can be induced by structural failure in the region about the nose, this effect is known to be a consistent flow phenomenon for missile bodies within the low Mach, high angle of attack regime. These conditions are typically encountered during the boost phase of a vertically launched missile. Many researchers have investigated the effects and properties of asymmetric flow as related to missile bodies. Experimental results indicate that flow separation commences at angles of attack of just a few degrees. At such relatively low incidence, the formation of lee side vorticity occurs in a symmetric and largely steady manner. At angles of attack of 25 degrees or more, asymmetric vortex development and shedding take place. While the asymmetric structure is nominally steady, a noted unsteady behavior is observed to occur at angles of attack near 55 degrees [Ref. 2]. Under certain flow conditions, the vortex pattern is known to rapidly fluctuate between nearly symmetric and highly asymmetric structures [Ref. 3]. The exact mechanism of asymmetric vortex generation about missile body configurations is not yet fully understood, although the general consensus of investigators links this phenomenon to Reynolds and Mach numbers, nose fineness ratio, and the angle of attack [Ref. 4]. It is interesting to note that asymmetric modeling usually requires the introduction of a perturbation about the nose region, thus creating conditions very similar to those experienced by the TVC ASROC.

The rapid application of new technologies towards improved capability and newly configured missiles demands a responsive method for the evaluation of design modification proposals. Such performance evaluations must include a comprehensive analysis of the dynamic factors which exist throughout the operating envelope of the weapon: increased maneuverability, high structural loads, high angle-of-attack aerodynamic effects, control surface limitations, and Mach number effects. By accurately modeling these conditions, the forces on and the moments about the missile body can be predicted and the flight trajectory estimated. A proper and complete description of the missile-flowfield interaction is both necessary and complex, but often must be approximated in a manner which permits a simplified application while still fulfilling the scope of the research effort. Such aeropredictive models rely on iterative mathematic computations and data base comparison, and are well suited for computer system implementation as a coded program.

A computer-driven solution can be based entirely on the theoretical relationships and derived equations that describe a body in motion through a fluid. Codes constructed in this manner are extremely complex, but may offer a precise numerical procedure for solution. Such numerical programs require a great amount of computer time, and remain largely within a research stage. Many of these numerical programs employ new modeling techniques or innovative computational schemes. Less complicated codes combine computations and relevant empirical results. There is a wide range in both the capability and modeling approach of codes within this category. These programs generally show a good degree of consistency with accepted experimental data or alternate codes.

The accuracy of any code is, at best, limited to the level with which the missile-flowfield interface has been modeled. A purely mathematical approach is conditionally capable of a complete solution, but may require exorbitant development costs and restrictive computer time. Furthermore, as these theoretical codes are somewhat tailored to specific applications, they may be sensitive to initial conditions and initial data inputs. These characteristics may make such a theoretical code untenable and undesirable for general purpose use. Semi-empirical methods seek a valid and accurate combination of computational mechanics and experimental observation, and are frequently developed on and extended to the smaller computer systems normally associated with research and academic institutions. Many semi-empirical programs currently in use are accurate to a level satisfactory for preliminary or intermediate design. While these codes are less capable than theoretical programs, they are easier and faster to operate, and afford the user a wide range of input options. Semi-empirical codes permit an accelerated preliminary design process, and can greatly reduce the amount of costly wind tunnel testing required during this phase. In view of the flexibility and efficiency to be gained, aeroprediction modeling codes have become essential tools for aerodynamic research and development.

B. OBJECTIVES

The objectives of this thesis are to research the available operational predictive missile codes and identify those suitable for installation and operation on the mainframe computer system at the Naval Postgraduate School, in support of the Weapons Engineering academic curriculum and current high angle of attack missile research. Acquired programs are to possess capabilities for modeling conventional missile configurations in both subsonic and supersonic Mach regimes. Force and moment prediction is to include analysis at high angle of attack, with the desired inclusion of asymmetric separation features. Predicted quantities for selected input data are to be compared and discussed for each code. Finally, simulations based on the geometry of a Standard-type missile model will be made and compared against Naval Postgraduate School wind tunnel data of this model, the testing of which supports an ongoing research effort for the Naval Surface Warfare Center at Dahlgren, Virginia.

II. PREDICTION PROGRAMS FOR AERODYNAMIC ANALYSIS

The capability and validity of a computational prediction code are primarily determined by the detail and depth to which the missile-flowfield interaction has been modeled. A program typically becomes more involved as consideration is given to complex and non-traditional configuration geometries, and is further compounded for application of nonlinear aerodynamic effects. The development of a satisfactory model cannot, however, be done irrespective of computer system requirements. The construction of an aeroprediction code should include the following criteria:

- flexibility as to allowable configuration geometries.
- applicability to a sufficiently broad range of flight conditions.
- accuracy at a level congruent with development objectives, research goals and operational requirements.
- run time and computer system requirements reasonably available to the intended user base.

Neglect in consideration of these factors may severely limit the operability of a program or render it altogether unsatisfactory.

Most aerodynamic prediction codes can be categorized as either theoretical or semi-empirical, and are discussed in this manner. A brief review of several techniques and modeling principles illustrates the fundamental differences of various methods, a well as similarities inherent to missile prediction codes. Selected operational codes are presented for comparison along these lines. A review of missile aerodynamics and operational prediction programs is given by Lacau [Ref. 5].

A. THEORETICAL PREDICTION CODES

Codes of this type perform a purely computational analysis based on numerical methods. Such programs model the governing partial differential equations (based on certain simplifying assumptions) by finite mathematics. These codes have shown excellent results when applied to three dimensional missile aerodynamics, and have provided investigators with valuable information pertaining to local flowfield characteristics and complex flow mechanisms [Ref. 6]. Although severe computer constraints currently limit the application of such programs, rapid advances in computer technology make the computational fluid dynamics code a promising approach for future work. Numerical methods of high incidence missile aeroprediction are developed using the Navier-Stokes

2.2 IMPLEMENTATION CHARACTERISTICS

One of the purposes of validating compilers is to determine the behavior of a compiler in those areas of the Ada Standard that permit implementations to differ. Class D and E tests specifically check for such implementation differences. However, tests in other classes also characterize an implementation. The tests demonstrate the following characteristics:

a. Capacities.

1) The compiler correctly processes a compilation containing 723 variables in the same declarative part. (See test D29002K.)

2) The compiler correctly processes tests containing loop statements nested to 65 levels. (See tests D55A03A..H (8 tests).)

3) The compiler correctly processes tests containing block statements nested to 65 levels. (See test D56001B.)

4) The compiler correctly processes tests containing recursive procedures separately compiled as subunits nested to 17 levels. (See tests D64005E..G (3 tests).)

b. Predefined types.

1) This implementation supports the additional predefined types SHORT_INTEGER, LONG_INTEGER and LONG_FLOAT in the package STANDARD. (See tests B86001T..Z (7 tests).)

c. Expression evaluation.

The order in which expressions are evaluated and the time at which constraints are checked are not defined by the language. While the ACVC tests do not specifically attempt to determine the order of evaluation of expressions, test results indicate the following:

1) Some of the default initialization expressions for record components are evaluated before any value is checked for membership in a component's subtype. (See test C32117A.)

2) Assignments for subtypes are performed with the same precision as the base type. (See test C35712B.)

3) This implementation uses no extra bits for extra precision and uses no extra bits for extra range. (See test C35903A.)

4) NUMERIC_ERROR is raised for integer comparison and membership tests except for smallest integer membership tests where no

equations, the Euler equations or the linearized potential flow equation (Prandtl-Glauert).

1. Navier-Stokes Methods

The Navier-Stokes equations should be capable of describing any flowfield over a missile body under any conditions. Predicted quantities include the effects of separated flow and rapidly fluctuating asymmetric vorticity. With very few exceptions, simplifications must be made to the full Navier-Stokes equations due to limitations in computer system resolution and an incomplete understanding of the physics of turbulence. Normally, the fluctuating components are time-averaged to yield the Reynolds-averaged equations. The Reynolds equations can be extended to the most complex flow conditions, however, a suitable turbulent flow model must be incorporated to provide closure of the solution, such as the algebraic method of Baldwin and Lomax [Ref. 7]. The Reynolds averaged equations can be further reduced to the thin-layer (neglecting streamwise viscous terms) or parabolized (neglecting unsteady terms and streamwise viscous diffusion) Navier-Stokes form. These equation types can be solved using time-marching and space-marching techniques for either turbulent or laminar flow conditions. A selection of Navier-Stokes codes is presented in Table 1 on page 6.

Table 1. NAVIER-STOKES MISSILE CODES

CODE NAME	CODE TYPE	LAMINAR TURBULENT	MACH REGION	GEOMETRY
ARC3D	FULL	LAMINAR AND TURBULENT	SUBSONIC TRANSONIC SUPERSONIC	CONVENTIONAL OR ARBITRARY
F3D	THIN LAYER	LAMINAR AND TURBULENT	SUBSONIC TRANSONIC SUPERSONIC	CONVENTIONAL OR ARBITRARY
NASBMG	FULL	LAMINAR AND TURBULENT	SUBSONIC TRANSONIC SUPERSONIC	CONVENTIONAL OR ARBITRARY
UWIN	FULL	LAMINAR	SUBSONIC TRANSONIC SUPERSONIC	CONVENTIONAL OR ARBITRARY
PNS	PARABOLIZED	LAMINAR	MACH > 1	CONVENTIONAL OR ARBITRARY
PNSFVM	PARABOLIZED	LAMINAR	MACH > 1	CONVENTIONAL OR ARBITRARY

Source: [Ref. 5, p. 1-43]

Of the relatively few Navier-Stokes codes in operation, one frequently applied is F3D, developed by Steger, Ying and Schiff [Ref. 8]. A thin layer, time accurate code, F3D has been used by Degani and Schiff to study three dimensional subsonic flow about a slender body of revolution at high angle of attack [Ref. 9]. For laminar flow, the coefficient of viscosity is taken from Sutherland's law, while turbulent conditions make use of an eddy-viscosity model introduced by Degani and Schiff [Refs. 10,11]. Further work has been done regarding vortex unsteadiness and the effects of spatial disturbances on vortex asymmetry at large incidence [Refs. 12,13]. Degani and Schiff report generally satisfactory computational results from F3D compared to experimental data, with computation times on the order of 30 seconds per iteration on a Cray supercomputer. Similar work has been done using an incompressible thin-layer Navier- Stokes code, FMC1. Hartwich and Hall, using an eddy-viscosity model based on the two-layer, zero-equation form of Baldwin and Lomax, have applied the FMC1 program to determine leeward pressure distributions on a tangent ogive body with large crossflow separation [Ref. 14]. Numerical solutions are good to excellent in comparison to experimental data, and represent an improvement to the results obtained using the F3D code with the turbulent flow model of Degani and Schiff. The required CPU times (per grid point per iteration at a Reynolds number of 2.0E5) are roughly 29 microseconds on a CDC Cyber 205 machine and 58 microseconds on a Cray 2. For low Mach regime analysis, the FMC1 code offers greater efficiency and increased accuracy over the F3D program, which appears to be characteristic of the incompressible flow codes. [Refs. 15,16,17].

2. Euler Methods

Euler equations represent the Navier-Stokes equations in which the viscous and conduction terms are ignored. Euler equations are descriptive of inviscid rotational or irrotational flow independent of Mach number. and can be applied to flow conditions with shock formation and vortex sheets. The steady equations are hyberbolic type partial differential equations, and are solved through space-marching techniques which restrict the application to supersonic speeds. The procedure for the solution of the unsteady equations is to advance the complete flow variable array in time until convergence occurs at some asymptotic limit; this approach is valid for both subsonic and supersonic Mach regimes, but neglects fluctuation terms induced by movement of the missile and associated flowfield changes. Various operational Euler codes are presented in Table 2 on page 8.

Table 2. EULER BASED MISSILE CODES

CODE NAME	EQUATIONS		METHOD	NUMERICAL SCHEME		MACH	
	STEADY OR UNSTEADY	CONSERVATIVE OR NON-CONSERVATIVE	FINITE VOLUME DIFFERENCES OR ELEMENTS	IMPLICIT OR EXPLICIT	CENTERED OR UN-CENTERED	< 1.0	> 1.0
EUFLEX	U	C	FV	BOTH	UC	YES	YES
EULBMG	U	C	FV	E	C	YES	YES
EULER3D	U	C	FV	E	C	YES	YES
EULSSM	S	C	FV	I	C	NO	YES
FLU3C	U	C	FV	E	UC	YES	YES
MISSILE	S	C	FD	E	C	NO	YES
MUSE	S	C	FD	E	C	NO	YES
SANDIAC	S	BOTH	FD	E	UC	NO	YES
SWINT	S	C	FD	E	C	NO	YES
WING2A	U	C	FV	E	C	YES	YES
ZEUS	S	C	FD	E	UC	NO	YES

Source: [Ref. 5, p. 1-44]

While not applicable to viscous flow analysis, Euler codes are powerful aeroprediction programs. Currently operational codes are capable of describing the flow conditions about any configurational geometry, including separated flow and shock formation effects. Two such codes are SWINT and ZEUS. These programs provide excellent accuracy through the use of finite difference solutions. Operator use is simplified in that a minimal amount of preliminary set up is required. Described as robust, both SWINT and ZEUS are receiving extensive use in missile aerodynamic prediction and design proposal performance evaluations. Techniques used in the structure of these codes, primarily the Godunov method of solution of the Euler equations, show particularly good results. Current work is in progress to expand such techniques to include viscous effects through application to Navier-Stokes equations. [Refs. 18,19,20].

Although reduced in complexity from the Navier-Stokes form, Euler codes require computer times on the order of comparable Navier-Stokes programs, and are normally not a viable method of conducting general aerodynamic analyses. A particular limitation exists in the solution of separated flow along a smooth surface, which requires the determination of cross flow separation lines for application of the Kutta condition. As appropriate nonlinear data bases are frequently unavailable, this information must be obtained through boundary layer flow solutions or from a suitable Navier-Stokes code.

3. Potential Flow Methods

The linearized potential flow equation provides a method to describe flow conditions with induced perturbation velocities slightly different than those in the freestream. Codes of this type are no longer purely numerical, reflecting instead an approximate mathematical form with certain simplifying assumptions required by the modeling approach. Most aeroprediction applications of the linearized potential equation are centered about a panel method. Panel methods are general numerical techniques used to describe flowfields about arbitrary bodies. While a large number of different applications have been developed, the vortex panel method is frequently used to evaluate the aerodynamic forces induced through missile-flowfield interaction.

Consideration is given to an arbitrary three dimensional body within an inviscid, incompressible flow. Vortex filaments are modeled as a vortex sheet, and the body surface is conceptually wrapped within this sheet. The approach is to explicitly solve for the vortex sheet strength (per unit length) such that the continuous conform of the body surface satisfies both the streamline conditions for the surrounding flow and the Kutta condition at the points of crossflow separation. In the absence of a closed form analytic solution, a numerical solution is obtained through the reduction of simultaneous equations. This requires approximating the vortex sheet as a series of panels about the body. The unknown vortex strength is taken as constant across each panel in first order solutions; higher order techniques model the panel strength functionally, such as a linear variation with surface displacement. The midpoint of each panel is selected as a control point at which boundary conditions of zero velocity of the crossflow normal component are enforced. The Prandtl-Glauert equations are used to determine the panel induced velocity at any point within the flow. Taken about each control point, a geometry dependent set of simultaneous equations is obtained which relates crossflow velocities to local panel vorticity. These equations, coupled with both the Kutta and streamline conditions, are solved to yield individual vortex sheet strengths. Flow tangency conditions are applied to determine the local variations in the flowfield above the sheet, which allows computation of pressure distributions and induced forces on the body.

The above procedure presents a valid scheme for the prediction of aerodynamic quantities on an arbitrary body in subsonic flow. A severe limitation exists, however, in that the linear nature of the solution restricts analysis to inviscid flow at low angles of attack. As such, application to separated flowfields is precluded due to the nonlinear mechanics of flow separation and vortex formation. The occurrence of flow separation, particularly at high angles of attack, causes a dramatic variation in both the strength and distribution of vortices, which in turn produces a wide fluctuation in the induced aerodynamic forces and moments. In view of the previously referenced firing exercises, the analysis of such flight conditions is obviously of considerable interest.

Work has been conducted in an attempt to extend panel methods to include nonlinear effects arising from vorticity and compressibility [Ref. 21]. Paneling techniques used to modify the linearized potential codes PFP1 through PFP5 have been applied by Van Tuyl for calculations about a missile at high angle of attack. The vortex wake is approximated by vortex sheets attached along pre-determined separation lines, with flow tangency conditions satisfied by the inclusion of source panels. Leeward pressure distributions are found to be in good agreement with thin-layer Navier-Stokes calculations and experimental data. The windward prediction results are inconclusive, with the values in good agreement with the empirical data base, but not with the Navier-Stokes solutions. [Refs. 22, 23]. Mendenhall and Perkins have conducted significant studies into the vortex-induced characteristics of missiles within nonlinear and unsteady flow conditions. This work, using vortex lattice panel methods and vortex cloud modeling, has shown that nonlinear effects can be captured using panel techniques, although the resulting code is quite complex and expensive to develop and run. The prediction code NOZVTX was found to accurately describe the separated flowfield to the leeside of a missile at a level suitable for engineering or preliminary design. It is interesting to note, however, that predicted values of windward pressure distribution show close agreement with experimental data, but are lacking to some degree in comparison with Navier-Stokes solutions, as was similarly reported by Van Tuyl. [Refs. 24,25].

The development of aeroprediction codes based on the linearized potential flow equations represents a departure from the purely theoretical structure of Navier-Stokes and Euler methods. In constructing these codes it becomes necessary to make critical assumptions and modeling approximations, such as in the distribution of panels and vortex strengths, the configuration of body contour relative to the freestream, and the determination of crossflow separation points. Errors in these input criteria may well result in distorted output to a point that meaningful interpretation is inhibited. While these codes are appreciably less involved than those derived from the wholly mathematical description, their approximate theoretical form is less precise. The results of these programs have been excellent, however, and certainly warrant further development. Although currently considered an advanced design tool, these codes will become increasingly useful as computer system capabilities continue to advance. A selection of linear potential equation codes is shown in Table 3 on page 12.

Table 3. LINEARIZED POTENTIAL BASED MISSILE CODES

CODE NAME	VORTEX SEPARATION	MACH	GEOMETRY
DEMON/LRCDM	BODY AND FIN VORTEX SEPARATION VORTEX MODEL WITH PANEL METHOD	$M > 1$	CONVENTIONAL OR ARBITRARY
DM3INL	FIN VORTEX SEPARATION WITH TRAILING EDGE WAKE RELAXATION VORTEX MODEL WITH PANEL METHOD	$M > 1$	CONVENTIONAL OR ARBITRARY
HOP		$M < 1$ $M > 1$	CONVENTIONAL OR ARBITRARY
NANC		$M > 1$	CONVENTIONAL OR ARBITRARY
NFKRSUB/SUP	BODY AND FIN VORTEX SEPARATION VORTEX MODEL WITH PANEL METHOD	$M < 1$ $M > 1$	CONVENTIONAL
NLRAERO		$M < 1$ $M > 1$	CONVENTIONAL OR ARBITRARY
NWCDM/NSTRN	BODY AND FIN VORTEX SEPARATION WITH TRAILING EDGE WAKE RELAXATION VORTEX MODEL WITH PANEL METHOD	$M > 1$	CONVENTIONAL
PANAIR		$M < 1$ $M > 1$	CONVENTIONAL OR ARBITRARY
PANEL		$M < 1$	CONVENTIONAL OR ARBITRARY
QRFL/DEMONI	BODY AND FIN VORTEX SEPARATION VORTEX MODEL WITH PANEL METHOD	$M < 1$ $M > 1$	CONVENTIONAL
WBC	BODY AND FIN VORTEX SEPARATION VORTEX MODEL WITH PANEL METHOD	$M < 1$	CONVENTIONAL OR ARBITRARY

Source: [Ref. 5, p. 1-45]

Theoretical programs offer the flexibility of unrestricted geometry configurations and the fundamental ability to accurately describe even the most complex missile-flowfield interactions. In addition to computational aerodynamic predictions, the modeling techniques offer important explanatory insight into the mechanics which exist for nonlinear flow. The employment of such codes is currently restricted to research facilities which possess the tremendous computer systems required, and is generally not a feasible option for basic design work or aerodynamic prediction. Until computer technology delivers these codes into wide distribution and commonplace use, smaller research institutions and academic concerns must rely on alternate means to conduct efficient and rapid preliminary evaluations of stability and performance.

3. SEMI-EMPIRICAL PREDICTION CODES

Semi-empirical codes are primarily designed to provide for rapid and efficient aerodynamic analysis of traditional or conventional configurations. These programs attempt to combine approximate theoretical relationships and empirical data such that the output agrees with observed experimental results. By excluding routines which attempt to interpret various flow parameters, such as the nonlinear mechanics of the high angle of attack regime, these methods can be greatly reduced in complexity as compared to theoretical models. Semi-empirical codes are intended for practical, general purpose analysis, and can normally be operated on computer systems considerably less capable than those required for numerical codes. The principal methods of semi-empirical codes are slender body and linearized potential flow theory, which are most often utilized in a component build-up approach.

The component build-up procedure calculates the individual aerodynamics of each elementary portion of the missile body, estimates the effects of component interaction, and attempts to synthesize a solution based on the total body. While this method is generally restricted to conventional configurations, a component build-up approach can offer significant reductions in development and usage costs, good to excellent accuracy for traditional missile geometries, easy extension to parametric analysis, and simple inclusion of experimental data [Ref. 26]. As the alternative to component build-up is a panel method geometry description, the majority of preliminary design missile codes are structured around a build-up procedure.

Semi-empirical aeroprediction programs can generally be separated into two distinct categories. One approach is an empirically oriented solution based on correlation to functional data for various component geometries, flight conditions, and angles-of-attack. The remaining technique is a more involved computational method based on crossflow modeling with the addition of body vortex theory. Several of the fundamental methods used are discussed below; a more complete background of empirical and semi-empirical routines has been prepared by Wardlaw [Ref. 27]. Various empirical and semi-empirical codes are presented in Table 4 on page 14.

Table 4. EMPIRICAL AND SEMI-EMPIRICAL MISSILE CODES

CODE NAME	MACH RANGE	INCIDENCE RANGE (DEGREES)	ROLL ANGLE (DEGREES)	AXIAL FORCE	STATIC STABILITY	DYNAMIC DERIVATIVES
ABACUS	M < 5.0	-90 to 90	-180 to 180		CN,Cm,Cn Cy,Cl	Cmq,Cmad Cnr,Clp
AERAM	1.2 < M < 5.0	0 to 30	0 to 45	CA,CAw CAf,Cab	CN,Cm	Cmq,Cmad
BAKER	0.6 < M < 3.0	0 to 180	0		CN,Cm	
CASAERO	M < 4.0	0 to 30	0		CN,Cm	Cmq,Cmad Cnr,Clp
DORRAM	M < 4.0	0 to 90	0 to 360	CA,CAw CAf,Cab	CN,Cm Cy,Cn	Cmq,Cmad Cnr,Clp
MAP	M < 8.0	0 to 15	0 to 90	CA,CAw CAf,Cab	CN,Cm Cy,Cn,Cl	
MISSILE DATCOM	M < 8.0	0 to 90	0 to 360	CA,CAw CAf,Cab	CN,Cm Cy,Cn,Cl	Cmq,Cmad Cnr,Clp
MISSILE ONERA	M < 4.0	0 to 25	0 to 360		CN,Cm Cy,Cn,Cl	
MISSILE 1	M < 4.0	0 to 45	0 to 360	CAw,CAf	CN,Cm Cy,Cn,Cl	
MISSILE 2	M < 5.0	0 to 45	0 to 90		CN,Cm Cy,Cn,Cl	
MISSILE 3	M < 4.5	0 to 45	0 to 90		CN,Cm Cy,Cn,Cl	
NSWC	M < 8.0	0 to 45	0 to 360	CA,CAw CAf,Cab	CN,Cm Cn,Cl	Cmq,Cmad Cnr,Clp
S/HABP	M > 2.0	-90 to 90	0 to 360	CAw,CAf	CN,Cm Cy,Cn,Cl	

Source: [Ref. 5, p. 1-42]

1. Empirical Methods

Empirical techniques for aerodynamic analysis are often simplified models of some frequently observed and well documented conditions. These routines attempt to replicate the experimental results through the proper use of data base information. Perhaps the most well known method for body alone aerodynamic prediction is the so called crossflow analogy of Allen and Perkins [Refs. 28,29]. In this method, the flow over a body at incidence is treated as the resultant of normal flow and crossflow components. The body normal force represents the inviscid, or potential flow contribution, and is calculated using slender body theory. The viscous crossflow term is evaluated through analogy to the flow about a cylinder, in which the crossflow drag coefficient of the body is equated to the steady state drag on the cylinder. Further work by Jorgensen has extended this method to transonic regimes for angles of attack up to 180 degrees. [Refs. 30,31]. Another empirical approach is the impulsive flow analogy of Kelly [Ref. 32]. In this method the crossflow about an inclined body is likened to the flow around an impulsively started cylinder. Specifically, the assumption is made that the crossflow plane is swept uniformly down the length of the body. The translation of the crossflow plane is viewed analogously to the leeside flowfield produced behind the inclined cylinder. Flowfield properties induced by the changing nose radius of the body are captured by allowing the cylinder to expand [Ref. 27, pp. 3-8]. Further work using this method has been done by Thomson in which an updated data base for impulsive cylinders (Sarpkaya) was available [Refs. 33,34]. Many variations of these models have been developed which incorporate adjustments so as to include the effects of more complex phenomena such as those related to boundary layer flow, base regions and nose bluntness.

A widely used operational code is MISSILE DATCOM of McDonnell Douglas [Refs. 26,35]. This program uses component build-up techniques to provide aerodynamic prediction for traditional missile configurations and arbitrary geometries. Static coefficient and dynamic derivative computations can be had for bodies at high angles of attack, but no analysis of asymmetric flow separation is possible. For conventional symmetric missile bodies, the effects of angle of attack are estimated using an extension of the Allen and Perkins method, as expanded by Jorgensen. Potential flow solutions are taken from the second order shock equations (SOSE), and Van Dyke hybrid theory; the viscous crossflow solutions are taken from correlation with empirical crossflow drag data of Messersmitt-Bolkow-Blohm. Configuration synthesis includes vortex tracking and strength calculations for body and lifting surface vortices. The development of the MISSILE DATCOM source code was largely driven by an extensive review and comparison of existing data bases and computational methods. This program has shown simple operation on a number of different computer systems, with compilation times on the order of several CPU seconds for CDC Cyber machines. While the accuracy of specific quantities is dependent on input geometry and flight conditions, the overall accuracy of the code is deemed to be at a level suitable to support general purpose, preliminary design studies.

A similar aeroprediction code has been developed by Devan, which will be referred to here as NSWC [Ref. 36]. Work on this program continues as an ongoing research project of the Naval Surface Warfare Center (NSWC), with the source code presently in a fourth stage of development. Current efforts are directed at extending the range of application to higher Mach and higher angle of attack flight regimes. Prediction accuracy for dynamic derivatives is being improved as well. The NSWC aeroprediction code is structured as a component build-up approach for axisymmetric, traditional missile and projectile geometries. This code offers the user a wide variety of options, but requires a more detailed input geometry than does MISSILE DATCOM. High angle of attack aerodynamics do not include consideration of asymmetrically separated flow, and are restricted to flight conditions above the subsonic regime. Crossflow modeling follows the Allen and Perkins approach. Inviscid flow solutions are taken from SOSE, Tsien first order methods, Wu and Aoyoma computational methods, and solution data for Euler equations. High angle of attack viscous solutions are derived from empirical crossflow data which are maintained on a separate tape or input file. Aerodynamic quantities are predicted with the accuracy required for preliminary or intermediate design analysis and performance evaluations. Compilation times (per reference flight condition) are in the CPU seconds for a CDC 865 Cyber machine.

2. Semi-Empirical Methods

Semi-empirical techniques attempt to model the flow conditions within the crossflow plane. Many of these models use potential flow theory, based on the impulsive flow description of leeside separation and trailing wake. As previously noted, the nonlinear potential equation can be reduced through the application of perturbation principles. If a slender body approach is assumed, the flow solution in the crossflow plane may be taken as incompressible which further reduces the linear velocity potential equation to a Laplacian form. The resulting linear partial differential equation is significantly easier to solve than the nonlinear full potential equation, but such linear, inviscid solutions are no longer exact and are not suitable for analysis in nonlinear regimes, i.e., transonic flight speeds at high angles of attack. Semi-empirical methods generally combine computational routines and empirical data with which the effects of leeside separation and vorticity can be accurately modeled.

Early semi-empirical techniques to analyze separated, nonlinear flow, made use of an impulsive flow model developed by Bryson [Ref. 37]. In this approach, point vortices are superimposed on the potential flow solution about a cylinder. Vortex wakes are assumed to roll up into concentrated filaments, which remain attached to the body by feeding sheets. Vortex strengths are determined by application of the Kutta condition along empirically determined separation points. The motion of vortices along the body length is such that the net force acting on the sheet and filament is zero, simulating an equilibrium condition between induced lift of the vortex and the pressure distribution across the sheet. Asymmetric separation can be modeled by introducing an initial perturbation to the vortex positions about the nose, although the manner in which this perturbation is applied is apparently a strong determinant in the properties of the resulting asymmetric flowfield. This approach has been further extended to body vortex models, such as in the work of Schindel and Wardlaw. [Refs. 38,39].

Other crossflow modeling work on viscous, unsteady flows has been conducted using multivortex or vortex cloud techniques. Numerous point vortices are used to represent each wake vortex in the leeside crossflow plane. The developing vortices are periodically introduced into the flowfield in the vicinity of crossflow separation points, and are modeled to roll up into large clusters of concentrated vorticity. Assuming that each point vortex maintains a constant strength after formation, vorticity transport equations can be taken from the Milne-Thomson circle theorem which allows calculation of vortex movement within the leeside flowfield [Ref. 40]. This approach was used by Angelluci to study symmetrically separated flows, and extended by Wardlaw to include asymmetric conditions [Refs. 41, 42]. Perhaps the most complete work is the discrete vortex cloud model of Mendenhall [Ref. 43]. Improved methods for vortex tracking and strength calculations have been developed by Nielsen, et al., which are frequently adapted for use in currently operational codes [Refs. 44,45].

An early semi-empirical method was developed by Fidler and Bateman [Ref. 46]. The basic approach couples a vorticity-conservation technique with a potential crossflow model. The effects of incidence on vortex strength and location are based on experimental data and theoretical results for both symmetric and asymmetric conditions. The model considers the strength and spacing of growing and shedding vortices. The first two vortices to form behind the nose are treated individually, with strength contributions from potential flow about the nose. As indicated by flow surveys, the solution method assumes that the remaining vortices are nearly equal in strength in relation to the boundary layer separation about the body. Solution of the first two vortices is taken from potential flow theory, while the so-called "street" vortices are evaluated using data on vortex strength as a function of angle of attack. This code achieves a fair degree of accuracy in the prediction of static coefficients and dynamic properties, although the onset of asymmetric vorticity is less satisfactory. Nielsen and Smith have developed a comprehensive and accurate model using similar methodology to describe vortex wake distributions for bodies at incidence [Ref. 47].

Codes which contain such semi-empirical computational schemes are normally developed for use in conjunction with panel method techniques. The mathematical routines require significantly increased computer memory and run time in comparison to more empirically oriented codes. Thus, the majority of such body vortex codes remain unsuitable for general research or preliminary design studies. An exception to this loose rule may be the VORSTAB II aeroprediction code. This semi-empirical code is primarily intended for fighter aircraft configurations, but includes the capability for missile geometry analysis. Both symmetric and asymmetric forebody separation are calculated using slender body theory and free vortex filament modeling. While symmetric vortex separation has been previously evaluated using vortex lattice techniques, the ability to accurately model asymmetric separation as an additional boundary value solution to a slender body, discrete vortex problem has only recently been demonstrated by Lan and Chin [Ref. 48]. To avoid the necessity of turbulent model Navier-Stokes solutions, boundary layer separation effects are evaluated through the use of nonlinear section data as introduced by Lan [Ref. 49]. This is accomplished in a iterative matching procedure of nonlinear section lift data and lifting surface theory. Although not currently in distribution, discussions with the investigators indicate that this very robust code is suitable for use on most computer systems, with approximately two megabytes (MB) required for an average compilation. [Ref. 50]. The dramatic reduction in computer system requirements to operate this highly capable code should significantly increase the level of aerodynamic research and design which can be routinely undertaken by both academic and industrial concerns.

III. SELECTION AND INSTALLATION

The selection process for aeroprediction codes was primarily influenced by the following factors: availability of the source code and documentation, compatibility of source code structure, language and operation time requirements generally consistent with the computer center facilities of this school, and a demonstrated capability for treatment of traditional missile configurations at high angles of attack. It was additionally desired that at least one code possess the ability to model asymmetric vortex shedding.

The availability of prospective programs was examined as regards to ownership of source coding, that is, public domain information versus reserved proprietary rights. Operational missile codes developed under federal (Defense Department) funding are not always public domain; innovative routines, data sets or modeling techniques may remain the property of the facility actually preparing and researching the source code. Proprietary source coding, if available at all, may have to be purchased, and may include restrictions on application and release.

The mainframe computer system at the Naval Postgraduate School is an IBM 3033/4381 Network. Operations exist to support high volume batch processing and general terminal timesharing for the students, faculty, staff and tenet commands. Terminal interactive use is performed by the two CPU 3033AP system, with 16 MB processor storage. Batch processing is accomplished by the 3033U and 4381-M1 combination. Programming languages include VS Fortran and Watfor 77. In addition to the IBM mainframe, VAX and micro-VAX workstations are available for use.

A. SOURCE CODE PROCUREMENT

In reviewing the literature concerning operational codes and computational methods, it became apparent that numerical programs and paneling techniques were not viable options for use with the available computer system. Nor were such codes particularly desired, in that the intended application is largely in support of introductory level aerodynamic research. As the majority of semi-empirical missile codes are roughly equivalent in capability, selection was more heavily influenced by availability.

In addition to the NSWC and MISSILE DATCOM codes, consideration was given to the data base oriented MISSILE 1, MISSILE 2 and MISSILE 3 codes of Nielsen Engineering and Research [Refs. 51, 52]. In that the MISSILE (1,2,3) codes provide little additional aerodynamic prediction, excepting an increase in allowable control deflection, the NSWC and MISSILE DATCOM programs were selected. The NSWC source code and documentation were obtained from Mr. Michael Armistead (G23), Naval Surface Warfare Center, Dahlgren, Va. The MISSILE DATCOM source code was provided by Mr. William Blake, Flight Dynamics Laboratory (AFWAL/FIGC), Wright-Patterson Air Force Base, Oh. Both of these codes have been used extensively to study the aerodynamics of missile bodies, and can be operated on the IBM 3033 system. Neither of these two codes, however, is capable of performing analysis of asymmetric vortex shedding at high angles of attack.

Identification of a suitable, asymmetric capable, aeroprediction code was a more difficult task. Nonlinear flow phenomena have normally been studied using higher order numerical techniques of the more complex research codes. Semi-empirical computational schemes have been described which are applicable to the asymmetric separation problem, but many of these approaches are either applied in paneling method codes, or left as modeling procedures unincorporated into complete operational missile codes. The VORSTAB II code may be ideally suited for application on the IBM 3033 or VAX systems. but is currently in restricted distribution and not available commercially. Through contact with Dr. Lan (University of Kansas Flight Research Laboratory) and Dr. Mehrotra (VIGYAN, Inc.), however, the possibility of obtaining a binary version of the VORSTAB II source code has been discussed. The availability of this code, in any format, would provide a greatly enhanced facility to conduct aerodynamic research and comparison to experimental data.

B. SOURCE CODE DESCRIPTION AND OPERATION

NSWC and MISSILE DATCOM were received on standard 9 track, formatted magnetic tapes spools. Each code was accompanied by a users guide, and a theory volume detailing the various computational methods, data bases, algorithm structure and subroutine functions. Test case input and output data were present for both pr ns. The aeroprediction codes were copied from tape to virtual machine disk in orde cilitate initial use related to installation and validation; subsequent operations are a ticipated to be performed in a batch mode. Preliminary work was conducted on th Watfor compiler. Compilation in Watfor requires that the source code adhere to much more stringent syntax and structure rules than is demanded by VS Fortran compilation. While such a cautious approach entails numerous, albeit relatively minor programming changes, inadvertant programming errors are greatly reduced. The conversion process additionally allows the operator to become acutely familiar with source code structure and subroutine function. This exposure becomes extremely beneficial when trouble-shooting is required on larger source codes.

1. NSWC

The NSWC program is written in ANSI Fortran, and structured in a top down executive manner. Various characteristics and subroutine methodology are presented in Table 5, Table 6 on page 22, and Table 7 on page 23; high angle of attack limitations are shown in Figure 1 on page 24.

Table 5. BODY ALONE METHODS OF THE NSWC AEROPREDICTION CODE

	MACH REGION			
COMPONENT	SUBSONIC	TRANSONIC	LOW SUPERSONIC	HIGH SUPERSONIC
NOSE WAVE DRAG	----	EULER PLUS EMPIRICAL	SECOND ORDER VAN DYKE PLUS MODIFIED NEWTONIAN	SECOND ORDER SHOCK EXPANSION PLUS MODIFIED NEWTONIAN
BOATTAIL WAVE DRAG	----	WU AND AOYOMA	SECOND ORDER VAN DYKE	SECOND ORDER SHOCK EXPANSION
SKIN FRICTION DRAG	VAN DRIEST II			
BASE DRAG	EMPIRICAL			
INVISCID LIFT AND PITCHING MOMENT	EMPIRICAL	EULER OR WU AND AOYOMA PLUS EMPIRICAL	TSIEN FIRST ORDER CROSSFLOW	SECOND ORDER SHOCK EXPANSION
VISCOUS LIFT AND PITCHING MOMENT	ALLEN AND PERKINS CROSSFLOW			

Source: [Ref. 36, p. 43]

Table 6. WING ALONE AND INTERFERENCE METHODS OF THE NSWC AEROPREDICTION CODE

COMPONENT	MACH REGION: SUBSONIC	TRANSONIC	LOW SUPERSONIC	HIGH SUPERSONIC
INVISCID LIFT AND PITCHING MOMENT	LIFTING SURFACE THEORY	EMPIRICAL	LINEAR THEORY	SHOCK EXPANSION AND STRIP THEORY
WING-BODY INTERFERENCE	SLENDER BODY THEORY AND EMPIRICAL		LINEAR THEORY SLENDER BODY THEORY AND EMPIRICAL	----
WING-TAIL INTERFERENCE	LINE VORTEX THEORY			----
WAVE DRAG	----	EMPIRICAL	LINEAR THEORY AND MODIFIED NEWTONIAN	SHOCK EXPANSION STRIP THEORY MODIFIED NEWTONIAN
SKIN FRICTION DRAG	VAN DRIEST II			
TRAILING EDGE SEPARATION WAKE	EMPIRICAL			
BODY BASE PRESSURE DRAG FROM TAIL FINS	EMPIRICAL			

source: [Ref. 36, p. 44]

Table 7. DYNAMIC DERIVATIVE COMPUTATION OF THE NSWC AEROPREDICTION CODE

	MACH REGION			
COMPONENT	SUBSONIC	TRANSONIC	LOW SUPERSONIC	HIGH SUPERSONIC
BODY ALONE PITCH DAMPING MOMENT	EMPIRICAL OR MODIFIED SLENDER BODY THEORY OR LINEAR INTERPOLATION OR NEWTONIAN THEORY			
WING AND INTERFERENCE ROLL DAMPING	LIFTING SURFACE THEORY	EMPIRICAL	LINEAR THIN-WING THEORY	STRIP THEORY
WING AND INTERFERENCE MAGNUS MOMENT	ASSUMED ZERO			
BODY ALONE ROLL DAMPING MOMENT	EMPIRICAL			
WING AND INTERFERENCE PITCH DAMPING	SLENDER WING OR NEWTONIAN OR LIFTING SURFACE THEORY OR STRIP THEORY OR EMPIRICAL			

Source: [Ref. 36, p. 44]

The source code is approximately 13,500 records in length. Extensive use has been made of named COMMON block variables and GO TO statements. This programming style allows a marked reduction in the overall source code size, but greatly increases the difficulty of troubleshooting and error tracing. The general absence of in-code documentation (comments) adds to this difficulty. The main program body is used to read input data, determine subroutine sequencing, and print the majority of output data. Data input is performed through the creation of a sequential, formatted input file. This method is lacking in that examination of the input file provides no direct information as to body configuration, flight conditions or run options. Such information is apparent only upon comparing the input file with the user manual. Compilation on the IBM system requires several CPU seconds, depending on the input configuration and the run options.

Aside from routine conversion errors, i.e., type specification mismatch, array dimensions, initialization, formatting, etc., the NSWC program required very few alterations to the source code. The majority of changes were connected to index arguments in loop structures, COMMON block variable declarations of different list element length, and precision checks on variable values used in bounded value functions, such as square root and hyperbolic functions. Validation of the NSWC program was made

(1) Body Geometry:

(i) body alone

(ii) body plus cruciform tail

(2) Mach Number Range: 0.8 to 3.0

(3) Angle of Attack:

(i) isolated component: 0 to 180 degress

(ii) body with tail: 0 to 45 degrees

(4) Tail Geometry:

(i) trapezoidal planform, edges parallel to axis

(ii) zero sweep trailing edge, parallel to base

(iii) leading edge sweep from 0 to 70 degrees

(iv) taper ratio 0 to 1.0

(v) aspect ratio (two fin) 0.5 to 2.0

(5) Nose Length: 1.5 to 3.5 calibers (pointed ogive)

(6) Afterbody Length: 6 to 18 calibers

(7) Total Span-to-Diameter Ratio: 1.0 to 3.33

Figure 1. High Angle of Attack Limits for the NSWC Aeroprediction Code

against 11 test case input/output data sets. These inputs represent a wide variety of standard configuration models used in aerodynamic research. The test case input is designed to cover the various input options allowable, and thus perform an operability check on nearly every subroutine. Of the 11 trial runs, the 9 involving ogive or conical nose sections were completed successfully, with good accuracy for all geometry parameters, structural loading values and aerodynamic quantities listed in the test case output. The blunt or truncated nose configuration output could not be replicated. For the given geometry and reference conditions, the pressure coefficients (with respect to axial body position) were seen to fluctuate in a seemingly random fashion. Discussions with Dr. Devan indicate that the problem may be related to the (double precision) accuracy of the solution as calculations are made to determine the second order Van Dyke jump conditions across slope and curvature discontinuities [Ref. 53]. It is felt that this problem can be corrected.

2. MISSILE DATCOM

The MISSILE DATCOM source code is written in ANSI Fortran, and has the appropriate syntax included to conform to the coding standards of both Fortran IV and Fortran V (Fortran 66 and Fortran 77) compilers. At roughly 42,000 records, the source code size represents the upper limit for manageable operation on the interactive timeshare net. Storage requires a single designated disk; as the source code is too large to edit as a single body, the program was subsequently divided into two separate files of equal length. Compilation involves copying both files to a temporary access disk, appending the files into the original source code, and executing the program. If changes must be made to the source code, the process must be repeated. The Watfor compiler, with the Release 31 option, is able to execute the program, although 4 MB and 20 cylinders of temporary access disk are required. During high volume loading of the interactive timesharing net, a routine compilation might be expected to exceed 25 minutes of real time. Initial installation and validation procedures were performed during low system usage periods.

MISSILE DATCOM is structured in a top down executive manner. Body alone methods are shown in Table 8 on page 26. Fin alone and configuration synthesis techniques are presented in Table 9 on page 27.

Table 8. BODY ALONE METHODS OF THE MISSILE DATCOM CODE

	MACH REGION		
COMPONENT	SUBSONIC	TRANSONIC	SUPERSONIC
NOSE WAVE DRAG	----	EULER PLUS EMPIRICAL	VAN DYKE HYBRID PLUS MODIFIED SECOND ORDER SHOCK EXPANSION
BOATTAIL WAVE DRAG	----	PAYNE CORRELATION	VAN DYKE HYBRID PLUS MODIFIED SECOND ORDER SHOCK EXPANSION
SKIN FRICTION DRAG	BLASIUS PLUS TRANSITION PLUS VAN DRIEST II		
BASE DRAG	MODIFIED SECOND ORDER SHOCK EXPANSION PLUS EMPIRICAL		
INVISCID LIFT AND PITCHING MOMENT	EMPIRICAL	EMPIRICAL	VAN DYKE HYBRID SECOND ORDER SHOCK EXPANSION
VISCOUS LIFT AND PITCHING MOMENT	BAKER PLUS JORGENSEN CROSSFLOW		

Source: [Ref. 26, p. 18]

Table 9. WING ALONE AND INTERFERENCE METHODS OF THE MISSILE DATCOM CODE

	MACH REGION		
COMPONENT	SUBSONIC	TRANSONIC	SUPERSONIC
INVISCID LIFT AND PITCHING MOMENT	LOWRY-POLHAMUS CORRELATION	R.A.S. DATA SHEET INTERPOLATION	SUPERSONIC WING THEORY
CARRY-OVER INTERFERENCE	NACA 1307		VIRA AND FAN CLOSED FORM ANALYTIC SOLUTIONS
WAVE DRAG	----	LINEAR FAIRING (FROM M = 1.05)	LINEAR THEORY SHOCK EXPANSION STRIP THEORY MODIFIED NEWTONIAN
SKIN FRICTION DRAG	BLASIUS PLUS TRANSITION PLUS VAN DRIEST II		
TRAILING EDGE SEPARATION	EMPIRICAL		
BODY BASE PRESSURE DRAG DUE TO TAIL FINS	EMPIRICAL		

Source: [Ref. 26, p. 70]

Data input is accomplished using a namelist construct. Although the namelist format is different than that required of Fortran compilers, a namelist emulator is incorporated into the code. This namelist input method is simple to use and allows a much better case documentation than sequential data input files. Control cards are available to specify which options are desired for the compilation. The MISSILE DATCOM test case provides input, output data for an arbitrary body-wing-tail missile. While this test case allows verification of certain principal subroutines, the complexity of this code is such that a more complete test series would prove beneficial. The majority of errors encountered during the validation procedure were related to variable type declaration, array dimensions, and COMMON block equivalence. The program has an internal error checking feature which is of great assistance in troubleshooting. The extensive use of documentation (comment) statements is excellent, and nearly essential in the maintenance of any large code. Only one structural change was necessary to facilitate compilation of the program. This alteration removed a logical condition from a subroutine call statement. The condition was deleted in order to allow variable loading and array initialization which were otherwise undefined.

The test case output data was matched with exceptionally good accuracy. This is due, in part, to the source code design which declares the majority of variables and subroutines as implicit double precision for non-CDC machines. One source of confusion is present in the user guide. As the "DAMP" option was not a control card input, dynamic derivative values are not listed within the test case output. Dynamic derivative output is shown, however, as a separate page to illustrate the format type. The reference conditions listed for this format example strongly suggest that the values reflect the output computation based on the test case input data, although these sums could not be replicated. Further ambiguity in the prediction of dynamic derivatives is discussed in the data comparison section of this paper; prediction methods are displayed in Table 10 on page 29.

Table 10. DYNAMIC DERIVATIVE METHODS OF THE MISSILE DATCOM CODE

	METHOD	
DERIVATIVE	BODY	FIN
CNq	USAF STABILITY AND CONTROL DATCOM	USAF STABILITY AND CONTROL DATCOM
Cmq	USAF STABILITY AND CONTROL DATCOM	USAF STABILITY AND CONTROL DATCOM
CNAD	USAF STABILITY AND CONTROL DATCOM	USAF STABILITY AND CONTROL DATCOM
CmAD		USAF STABILITY AND CONTROL DATCOM
Cmq + CmAD	ERICSSON (LMSC)	Cmq + CmAD
CYp	ARDC SPINNER CODE (SPIN-73)	
Cnp/sin(alpha)	ARDC SPINNER CODE (SPIN-73)	
Clp	ARDC SPINNER CODE (SPIN-73)	

Source: [Ref. 26, p. 106]

IV. COMPARISON OF PREDICTION AND RESULTS

Following installation and successful test case validation procedures, each aeroprediction code was prepared for comparison runs. In order to permit a meaningful interpretation of source code performance, an acceptable experimental data base was required as a benchmark for each trial run; comparison between the MISSILE DATCOM and NSWC programs was dependent on a common description of body geometry under equivalent reference conditions.

Trial run inputs were selected from the test case validation section of the NSWC program users guide [Ref. 54]. This input data covers a sufficiently wide variety of missile and projectile configurations, and is accompanied by experimental wind tunnel and range data for the appropriate flight conditions. Wind tunnel data and geometry inputs of the Aeronautics and Astronautics Department Standard-type missile model were also available. The following sections provide a comparison of NSWC and MISSILE DATCOM source code predictions of various aerodynamic coefficients.

A. ARMY-NAVY SPINNER

The Army-Navy Spinner is a spin stabilized projectile geometry which is illustrated in Figure 2. The comparison trials were made at zero angle of attack with no roll angle and no control deflections; Mach condition was incremented from subsonic to high supersonic. Geometry inputs to both programs were identical, excepting rotating band height and spin stabilization, which can not be included into the MISSILE DATCOM input file. The comparison experimental data appearing in Figure 3 through Figure 6 are from Arnold Engineering and Development Center (AEDC) [Ref. 55].

1. Normal Force Coefficient Derivative

The prediction values of the normal force coefficient slopes are presented in Figure 3 on page 32. The NSWC curve is seen to follow the AEDC data fairly well, although underprediction and overresponse are present in the transonic region. Prediction accuracy improves with higher Mach numbers.

The MISSILE DATCOM prediction curve reflects the general form of the AEDC data and the NSWC curve, but shows a continuous underprediction in all Mach regions. Prediction within the transonic region is a better fit, in magnitude, than the NSWC code, but appears to lag slightly behind as a function of Mach number. The rapid increase in slope at the transonic-supersonic juncture is only partially present.

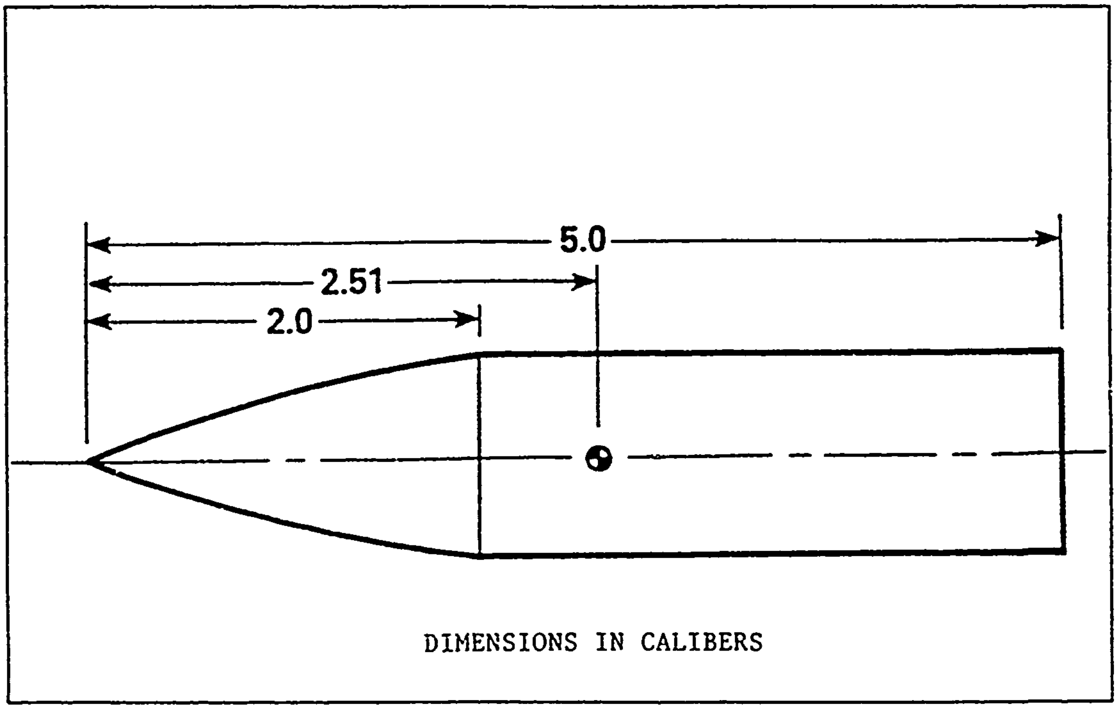

Figure 2. Army-Navy Spinner [Ref. 54, p. 42]

The discrepancy in prediction between these codes is most probably a result of the different methods used to calculate normal force and pitch damping coefficients. Within the transonic region, the NSWC code employs an improved method of Nielsen Engineering and Research (NEAR) [Ref. 56]. This method, which is restricted to constant radius afterbodies of five caliber length of less, is based on (one degree angle of attack) normal force and pitch moment solution data of the Euler equations. Using a least squares functional fit to a truncated Taylor series expansion, pressure distribution is interpolated from the various configuration grid data as determined by NEAR. The original interpolation scheme has been improved by augmenting the functional form fit data with computations from an improved Van Dyke Hybrid potential model for the transonic-supersonic crossover point. This additional data were generated from a much larger data base, and significantly improves the accuracy, since not all of the NEAR Euler solutions were completely convergent. A less accurate method of Moore is retained for use with afterbodies exceeding five calibers [Ref. 57]. [Ref. 36, pp. 32-43, 64]. The action of this computational method is clearly seen at the Mach 1.2 portion of the NSWC curve in Figure 3.

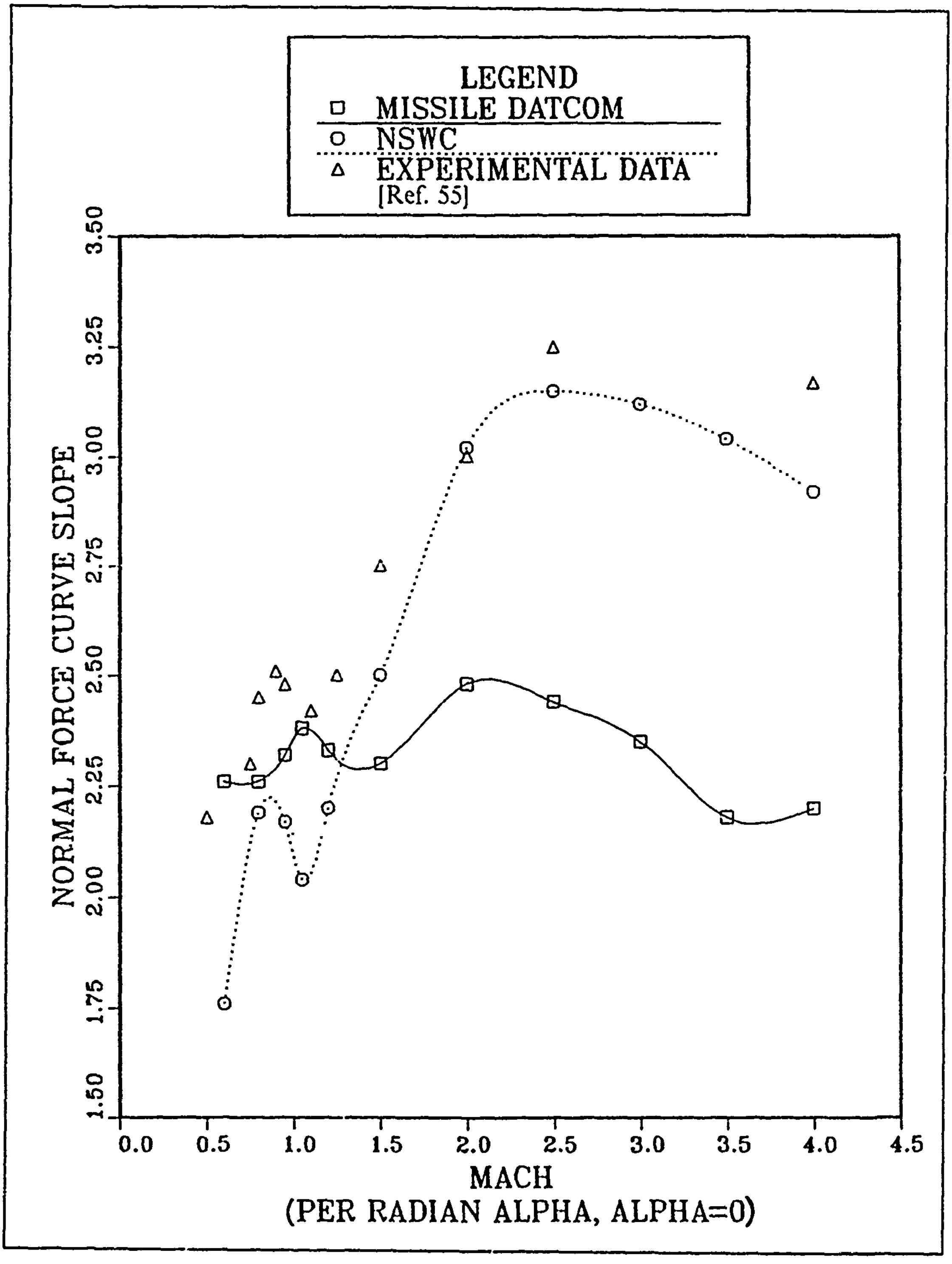

Figure 3. Normal Force Curve Slope Comparison for the Army-Navy Spinner

The MISSILE DATCOM program uses empirical methods to estimate the normal force and pitch moment coefficients in the subsonic and transonic regions; modified second order shock expansion and Van Dyke Hybrid techniques are incorporated for supersonic Mach. The NEAR method of Ref. 56 was considered during preliminary feasibility recommendations, but was rejected in view of the wider range of fineness ratios available from the empirical Messersmitt-Bolkow-Blohm (MBB) data sheets. The MISSILE DATCOM algorithms are reportedly far superior to those found in the NSWC code; however, this claim is not supported by the trial run comparison of the Army-Navy Spinner. [Ref. 26, pp. 19-20, 30-32].

2. Center of Pressure

NSWC and MISSILE DATCOM prediction curves for the center of pressure are shown in Figure 4 on page 34. The prediction data are plotted as a ratio to body length, and referenced 2.51 calibers from the nose tip. The prediction curves are similar in form to those in Figure 3, which is expected in light of the previous discussion. Prediction performance of both codes is somewhat poor for subsonic and low transonic Mach number. Significant underprediction error is again evident in the MISSILE DATCOM predictions within the supersonic region.

3. Drag Coefficient

The zero angle of attack drag predictions are presented in Figure 5 on page 35. As can be seen, both NSWC and MISSILE DATCOM show close correlation to the AEDC experimental data. This level of agreement is not unexpected, however, in that both programs use similar computational methods for nose and body components. Transonic prediction is performed by an improved wave drag prediction model of NEAR [Ref. 58]. This technique estimates drag effects through interpolation of pressure distribution data generated by time asymptotic solutions of the Euler equations. The data set of pressure distributions was developed from a family of tangent ogives for transonic Mach numbers. Short nose and small bluntness computations have been improved by recomputing wave drag with the RAXBOD program [Ref. 59]. Supersonic prediction is accomplished through a potential flow or a second order shock expansion method. The second order Van Dyke and modified second order shock expansion techniques of the NSWC code provide a better fit for supersonic Mach predictions, with drag coefficient estimates nearly coincident with the experimental data. [Ref. 36, pp. 27-29, Ref. 26, pp. 23-26].

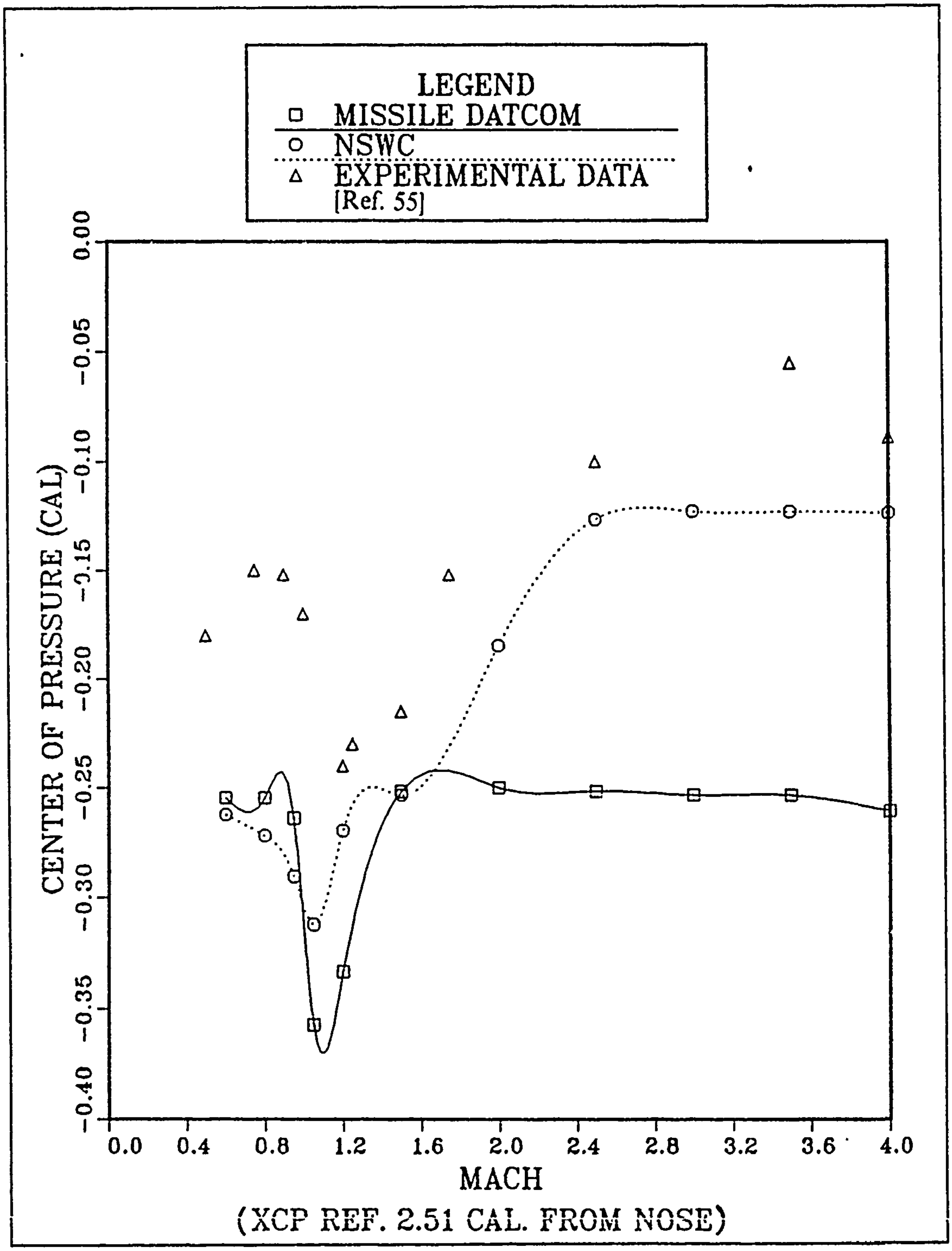

Figure 4. Center of Pressure Comparison for the Army-Navy Spinner

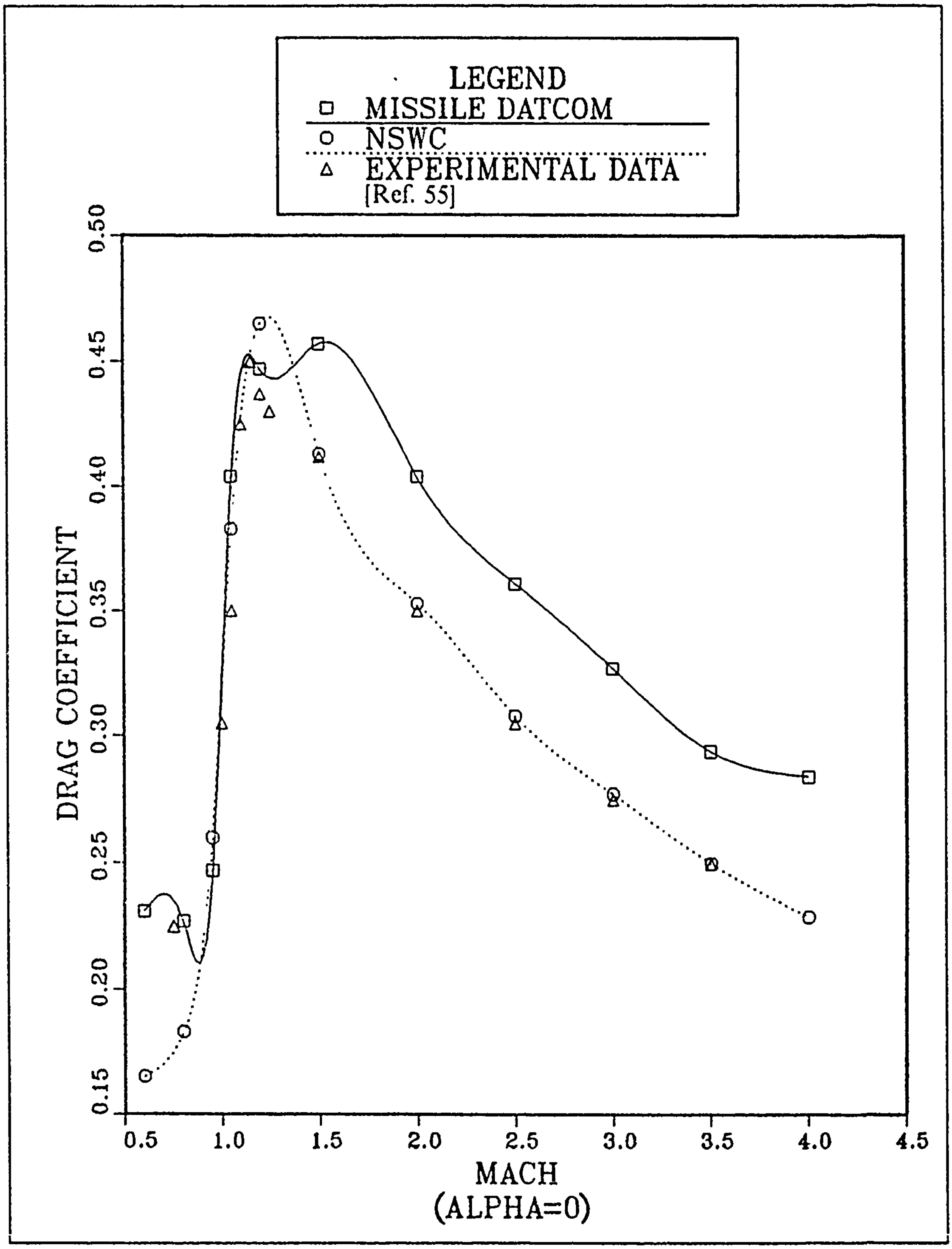

Figure 5. Drag Coefficient Comparison for the Army-Navy Spinner

4. Pitch Damping Coefficient

The NSWC, MISSILE DATCOM and AEDC pitch damping coefficient data appear in Figure 6 on page 37. The MISSILE DATCOM prediction values have been increased by a factor of two to account for differences in the non-dimensional definition of the pitch damping coefficient. Predicted values of the two codes are nearly identical in the subsonic region, although the fit is marginal in comparison to the AEDC data. Low supersonic prediction of the NSWC code is superior to that of MISSILE DATCOM; however, neither program offers a particularly accurate estimate within the supersonic region. The divergence of the two prediction code curves may result from the different computational methodology.

Dynamic derivative prediction of the NSWC code is strictly valid for low angles of attack. The prediction technique is a modified application of the LMSC method of Ericsson [Ref. 60]. The LMSC method has shown good accuracy for subsonic and transonic regions, where slender body theory remains applicable. Accuracy is diminished at supersonic Mach numbers, however, since boattail and afterbody effects are not considered. In order to reduce the prediction error within the supersonic region, the potential flow construct is assumed invalid, and solution is supplemented by strip theory. While this modified LMSC approach is adequate for most conditions, the prediction method is further augmented by an empirical process derived from wind tunnel and ballistic range test data on spin stabilized projectiles. This program is known as SPINNER or SPIN-73 [Ref. 61]. For body alone configurations, the NSWC code is structured to compare prediction values of the LMSC and SPINNER methods; if the LMSC predicted pitch damping coefficient is less negative and not within 75 percent of the SPINNER value, the SPINNER value is chosen. The effect of this empirical method results in the significant difference between the NSWC and MISSILE DATCOM prediction values at supersonic Mach numbers. [Ref. 36, pp. 21-25, 58].

The MISSILE DATCOM code uses a follow-on version of the LMSC method, but does not incorporate any compensating modifications for the prediction of pitch damping coefficients [Ref. 62]. The SPINNER routine is present, but contributes only to the solution of yawing moment, rolling moment and side force due to roll rate, as shown in Table 10 on page 29.

B. BASIC FINNER

The Basic Finner model is a cone-cylinder body with tail configuration as presented in Figure 7. Comparison computer runs were conducted at zero degree angle of attack

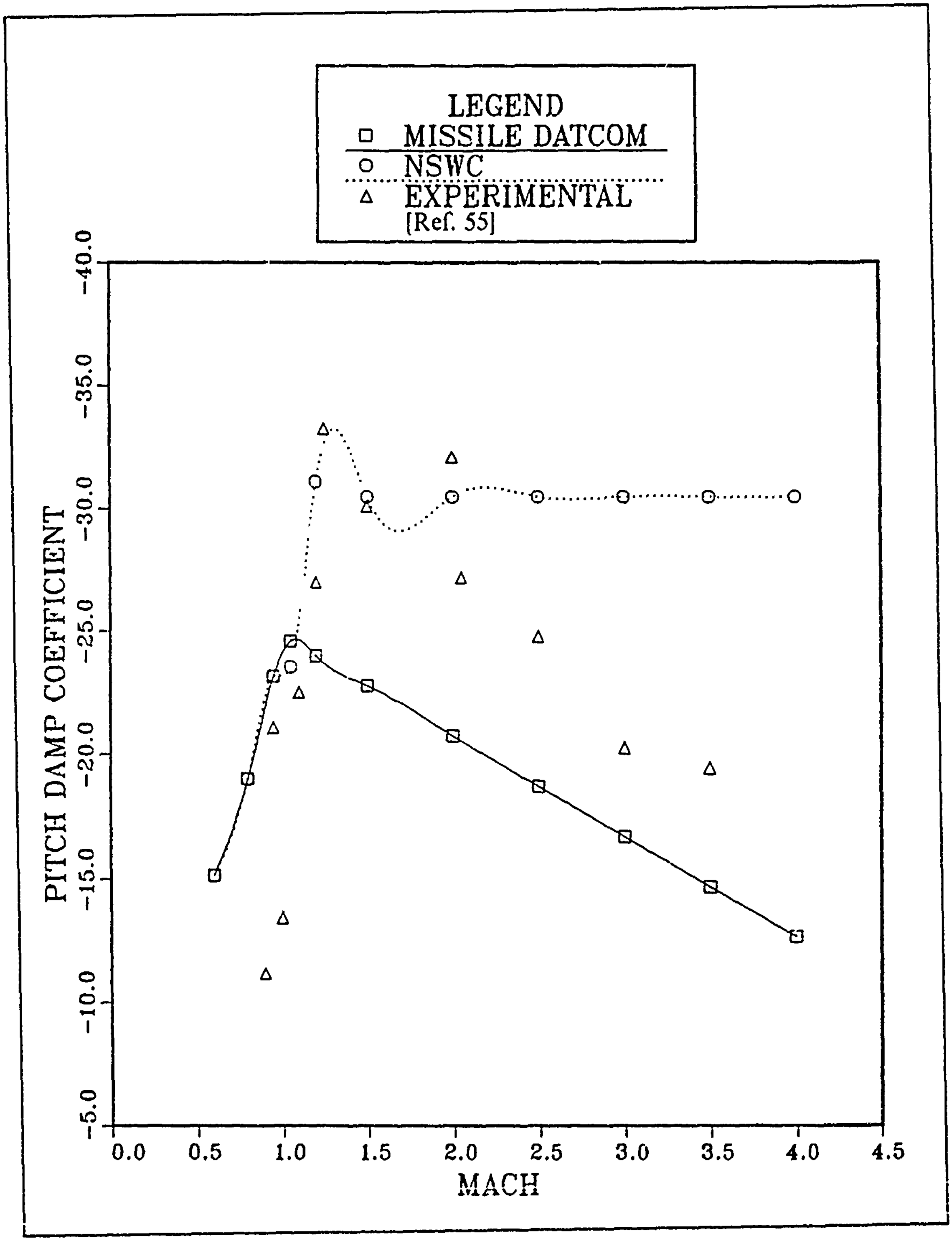

Figure 6. Pitch Damping Coefficient Comparison for the Army-Navy Spinner

with no control deflection and no roll angle. Input conditions included subsonic, transonic and supersonic Mach numbers. The experimental data in Figure 8 through Figure 11 are from a Bureau of Weapons technical report [Ref. 63].

1. Normal Force Coefficient Derivative

The NSWC and MISSILE DATCOM prediction values are plotted against the experimental data in Figure 8 on page 40. The prediction curves of both programs show a fairly accurate fit with the experimental data. The MISSILE DATCOM predictions are noticeably superior to the NSWC values, and are nearly identical to the experimental results within the supersonic region. The NSWC curve reflects a roughly constant underprediction error for all Mach numbers. While both codes show a greatly improved prediction capability relative to the Army-Navy Spinner projectile of Figure 3, it is apparent that the MBB data used by MISSILE DATCOM are particularly better suited for application to more traditional missile geometries. The NSWC code shows some underprediction error for both the Spinner and Basic Finner configurations.

2. Center of Pressure

The center of pressure comparison is shown in Figure 9 on page 41. Coefficient values are expressed as ratios to body length, referenced 6.10 calibers from the nose. The prediction accuracy of the NSWC and MISSILE DATCOM codes is excellent, especially within the low supersonic Mach region. As with the normal force derivative predictions, the estimation of center of pressure coefficients shows dramatic improvement from the Army-Navy Spinner case. The increased accuracy is most pronounced for the MISSILE DATCOM output. Both programs reflect an underprediction trend within the high supersonic region, although to a much smaller degree than for the Army-Navy Spinner comparison of Figure 4. The NSWC code provides a better functional fit for transonic Mach numbers.

3. Drag Coefficient

Prediction curves and experimental data of zero degree angle of attack drag coefficients are presented in Figure 10 on page 43. Both programs are seen to underpredict drag coefficient magnitude within the transonic Mach region, although the NSWC curve provides a better fit than does the MISSILE DATCOM curve. The prediction accuracy of each code improves for supersonic Mach numbers, with the NSWC prediction curve maintaining a better correlation to the experimental data. The quality of drag coefficient prediction is significantly reduced as compared to the Army-Navy Spinner projectile of Figure 5. As previously discussed, the NSWC and MISSILE DATCOM codes employ nearly identical computational methods for nose and cylinder drag calcu-

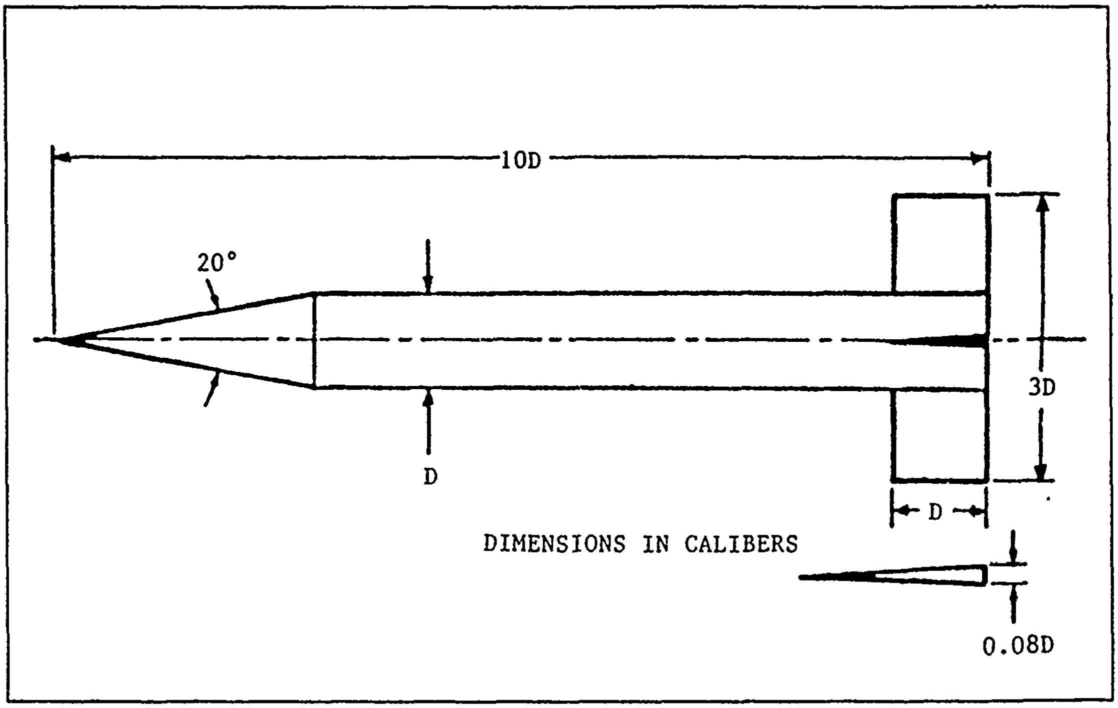

Figure 7. Basic Finner [Ref. 54, p. 53]

lation. While a reduction in prediction accuracy might be expected as the complexity of the geometry increases, it is reasonable to assume that the reduced similarity between the NSWC and MISSILE DATCOM drag predictions results from the calculation methods for wing alone drag effects. Both prediction programs utilize identical empirical methods for fin alone computations of trailing edge separation drag and skin friction drag. A difference exists, however, in the calculation of wave drag effects. The MISSILE DATCOM code employs the methodology of Moore in both the transonic and supersonic Mach regions [Ref. 64]. Transonic wave drag is estimated through a potential flow solution at Mach number 1.05, which is then linearly reduced as a function of Mach number. The supersonic technique is a computational grid solution using potential flow theory. [Ref. 26, pp. 70-75].

The NSWC program uses these same methods of Moore, but only within the supersonic Mach region; transonic wave drag effects are estimated using an empirical method. From the comparison of drag prediction in Figure 10, it is concluded that the empirical method of the NSWC code is superior to the approximate potential flow (lin-

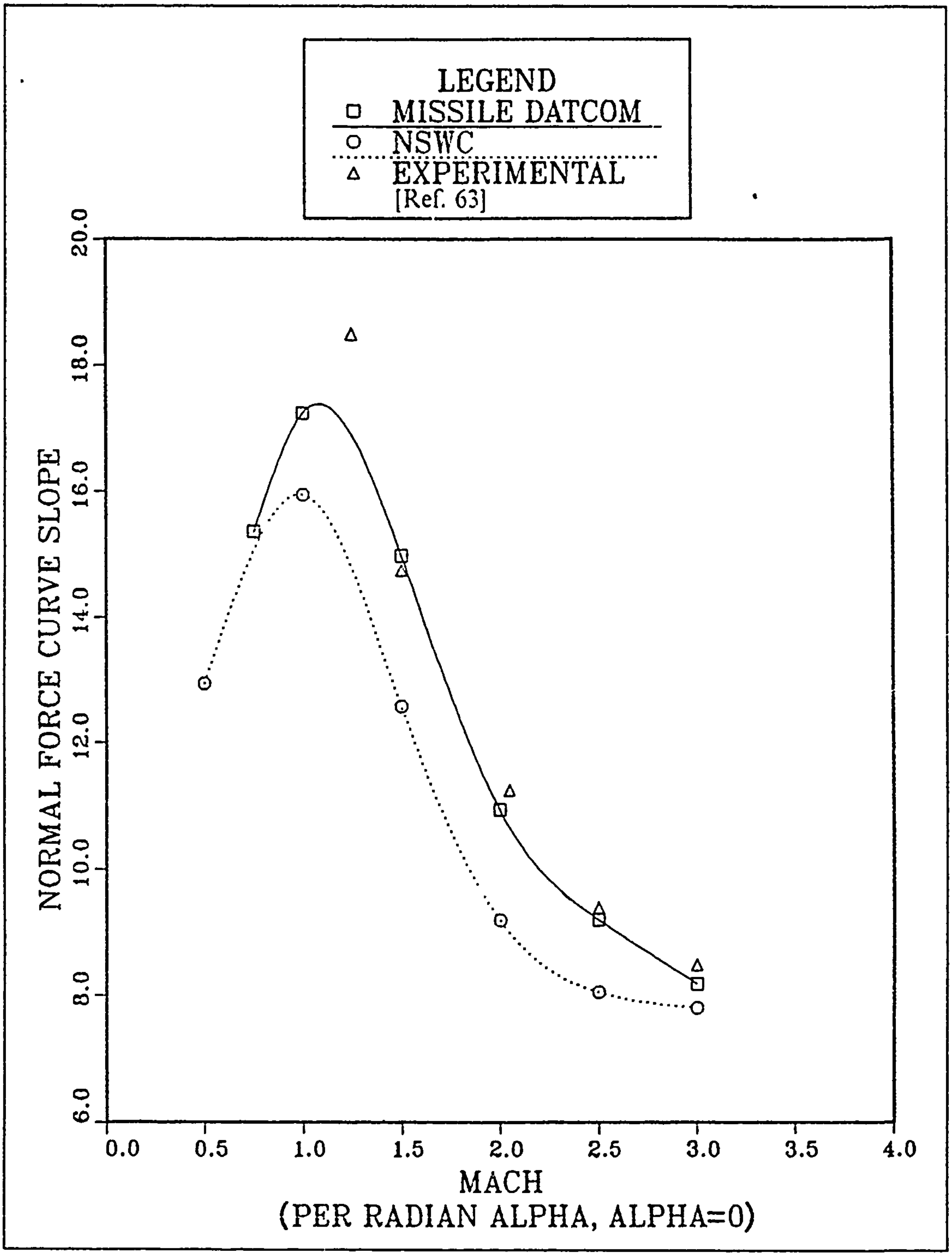

Figure 8. Normal Force Curve Slope Comparison for the Basic Finner

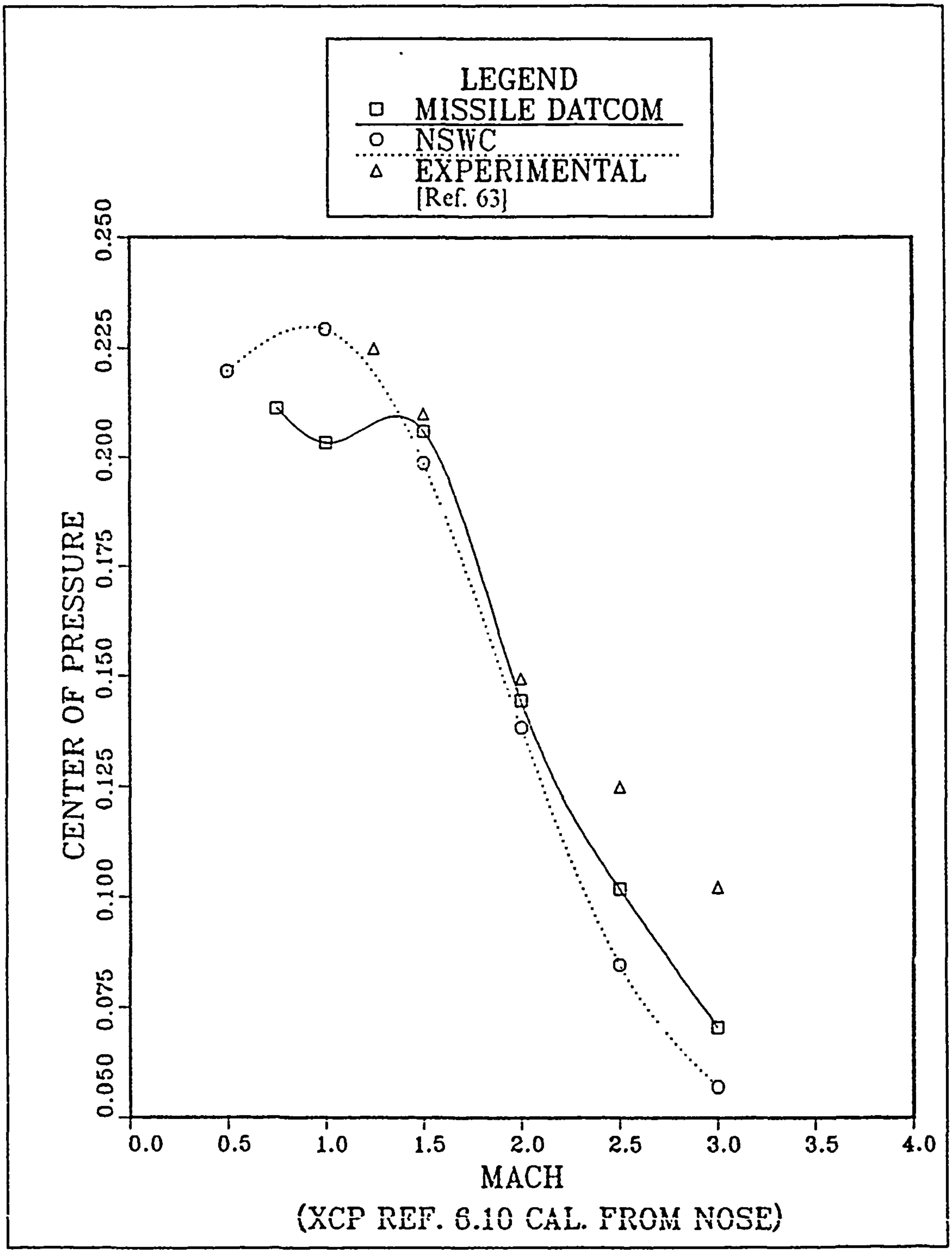

Figure 9. Center of Pressure Comparison for the Basic Finner

ear fairing) method of the MISSILE DATCOM code for drag coefficient estimation at transonic Mach numbers.

4. Pitch Damping Coefficient

Pitch damping coefficient predictions are presented in Figure 11 on page 44. While the NSWC curve reflects a fairly accurate image of the experimental data, it is obvious that the MISSILE DATCOM values are seriously underpredictive. Upon compilation of the MISSILE DATCOM comparison case for Basic Finner, an examination of the source code was conducted in an effort to uncover possible structure errors. The inclusion of an installation related error was considered a possibility, especially since no dynamic derivative calculations are included in the MISSILE DATCOM validation test case. The inspection of the source code failed to reveal any obvious errors or inadvertent alterations.

In reviewing the MISSILE DATCOM Final Report (Ref. 26), a figure containing pitch damping prediction data for the Basic Finner was located. The model geometry is also shown, and is identical to the input configuration for the comparison runs. MISSILE DATCOM prediction values and experimental data are plotted in this figure for two different moment reference positions; however, the prediction values could not be replicated with subsequent compilations of the MISSILE DATCOM source code. Furthermore, the unreferenced experimental data are significantly different from the data of Ref. 63 which appears in the NSWC User Manual. Finally, the MISSILE DATCOM Basic Finner comparison values presented here in Figure 11 appear similar to neither the experimental data nor program output curves shown in the figure on page 63 of the MISSILE DATCOM Final Report.

A further attempt to resolve these discrepancies was made using a dynamic derivative output sheet on page 123 of the MISSILE DATCOM User Manual (Ref. 35). Although these data are not part of the validation test case, an examination of the flight conditions and reference quantities for these data strongly suggests that the dynamic derivative values reflect prediction output for the test case input geometry. The test case was rerun accordingly, with the dynamic derivative control card option; however, the User Manual values could not be generated. It is somewhat interesting to note that the magnitude of error for this test case run is roughly equivalent to that experienced for the Basic Finner comparison. While this problem requires further attention, the validity of the experimental Basic Finner data (Ref. 63) used by the NSWC program has been confirmed through alternate sources [Refs. 65,66]. No interpretation or comparison of the MISSILE DATCOM pitch damping coefficient prediction data is offered. The

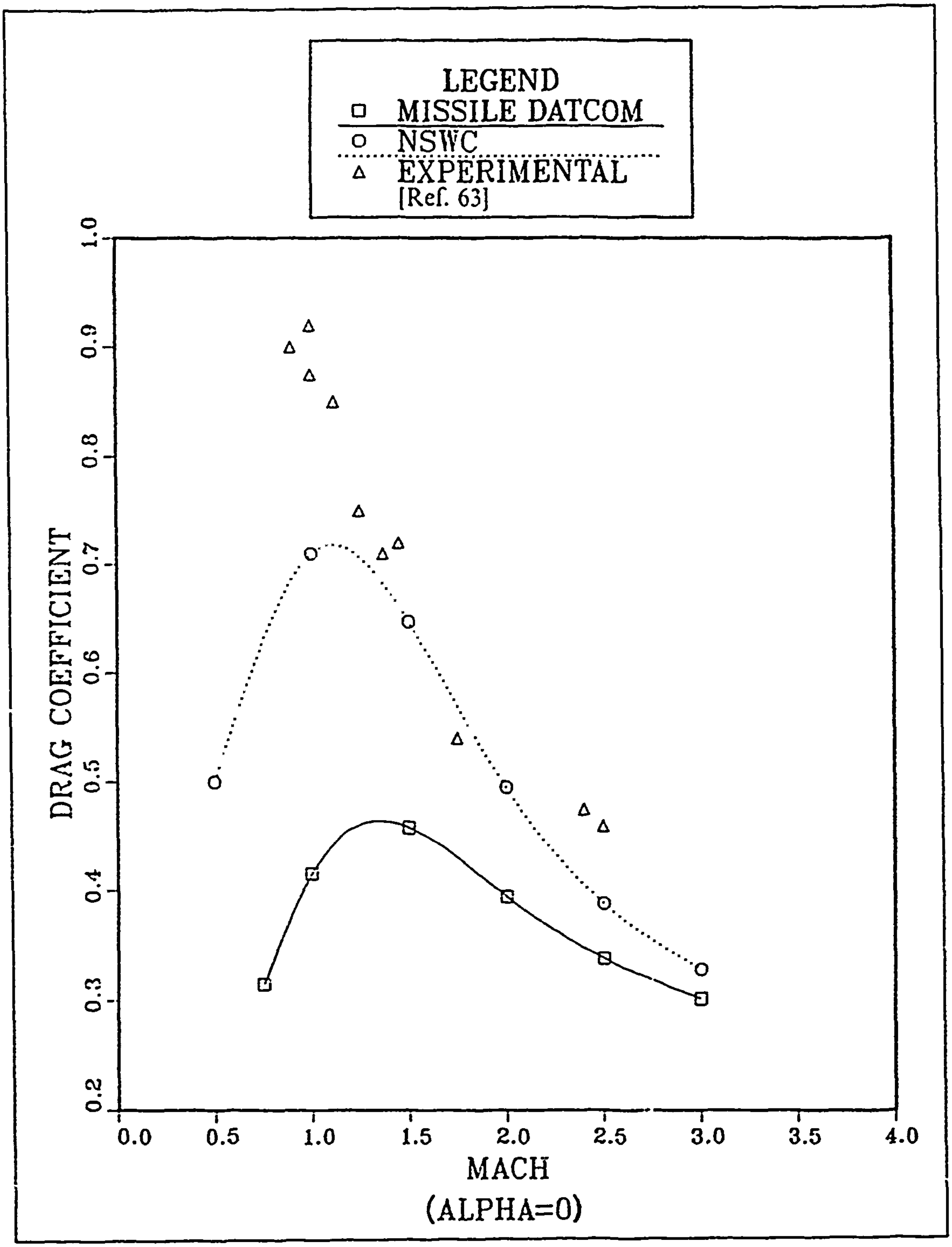

Figure 10. Drag Coefficient Comparison for the Basic Finner

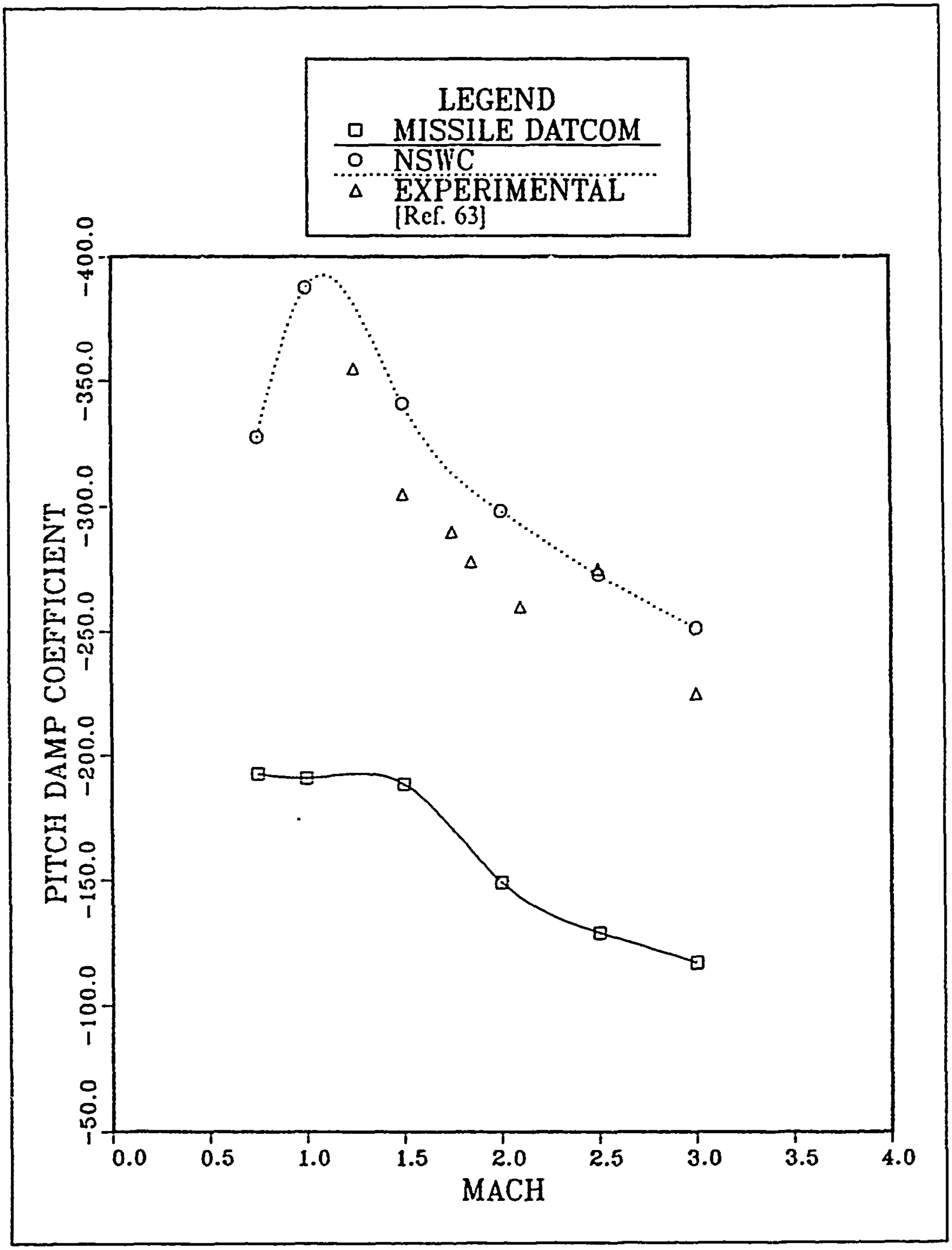

Figure 11. Pitch Damping Coefficient Comparison for the Basic Finner

MISSILE DATCOM User Manual pitch damping output and the Final Report figure of Basic Finner pitch damping coefficient prediction are enclosed in Appendix A and Appendix B.

C. AIR SLEW DEMONSTRATOR

The Air Slew Demonstrator is a tangent ogive body with tail as illustrated in Figure 12 on page 46. The comparison runs were made at low supersonic speed ($M = 1.3$) for angles of attack between 0 and 50 degrees. Control deflection and roll angle were not considered for normal force and center of pressure predictions; roll moment was predicted for a roll angle of 22.5 degrees. The experimental data shown in Figure 13 through Figure 15 are from AEDC [Ref. 67].

1. Normal Force Coefficient

Normal force coefficient predictions are presented in Figure 13 on page 47. Both the NSWC and MISSILE DATCOM prediction curves show a good degree of accuracy relative to the experimental data. The NSWC prediction values appear to reflect a roughly constant underprediction; the MISSILE DATCOM curve shows an overprediction trend which is largest between 25 and 45 degrees. The NSWC code uses a Martin Marietta empirical routine for the estimation of high angle of attack effects [Ref. 68]. The high angle of attack data set is maintained as a separate input file or tape. MISSILE DATCOM incorporates the Allen and Perkins plus Jorgensen crossflow method to approximate high angle of attack effects. This technique provides generally accurate predictions, with a maximum deviation from experimental data in the 15 to 60 degree angle of attack range [Ref. 26, pp. 30-31.]. The comparison of normal force coefficients for the Air Slew Demonstrator indicates that the NSWC and MISSILE DATCOM programs are quite comparable for transonic, high angle of attack conditions. The NSWC code appears to provide a marginally better estimate of the nonlinear trend at angles of attack greater than 25 degrees, which is an incidence angle normally associated with the onset of asymmetric vortex shedding.

2. Center of Pressure

Center of pressure coefficient predictions appear with the AEDC experimental data in Figure 14 on page 48. These data are expressed as ratios to the body length, referenced 4.33 calibers from the nose. Unlike the zero degree angle of attack comparisons, the high angle of attack predictions of center of pressure are, at best, considered fair to marginal. The NSWC curve fails to represent the experimental data for angles of attack less than 30 degrees; higher angle of attack estimates are overpredicted but of a

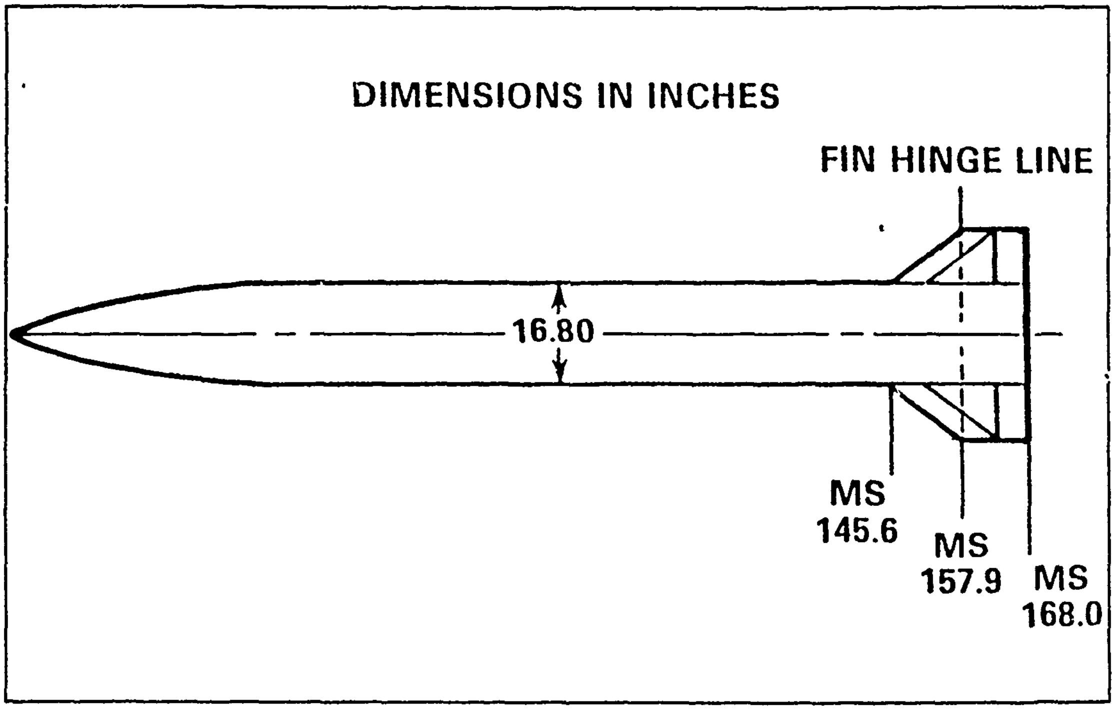

Figure 12. Air Slew Demonstrator [Ref. 54, p. 60]

functional form similar to that of the experimental data. While the MISSILE DATCOM curve is overpredictive for all angles of attack, the accuracy is improved below 15 degrees angle of attack. The parabolic form of the NSWC curve between 5 and 25 degrees is significantly in error relative to the experimental data and the MISSILE DATCOM predictions.

3. **Roll Moment Coefficient**

Roll moment calculations were made with a 22.5 degree roll angle input. The NSWC and MISSILE DATCOM predictions are presented with experimental data in Figure 15 on page 50. The NSWC program uses an empirical data base for roll moment prediction, while MISSILE DATCOM employs the SPIN-73 program. Roll moment estimations are of the right order of magnitude for both programs, but neither code is particularly accurate. The MISSILE DATCOM curve shows a significant overprediction trend as a function of increasing angle of attack. The NSWC curve shows a superior prediction capability at higher angle of attack, which is indicative that the empirical data base of the NSWC code provides better accuracy than the SPIN-73 routine at high an-

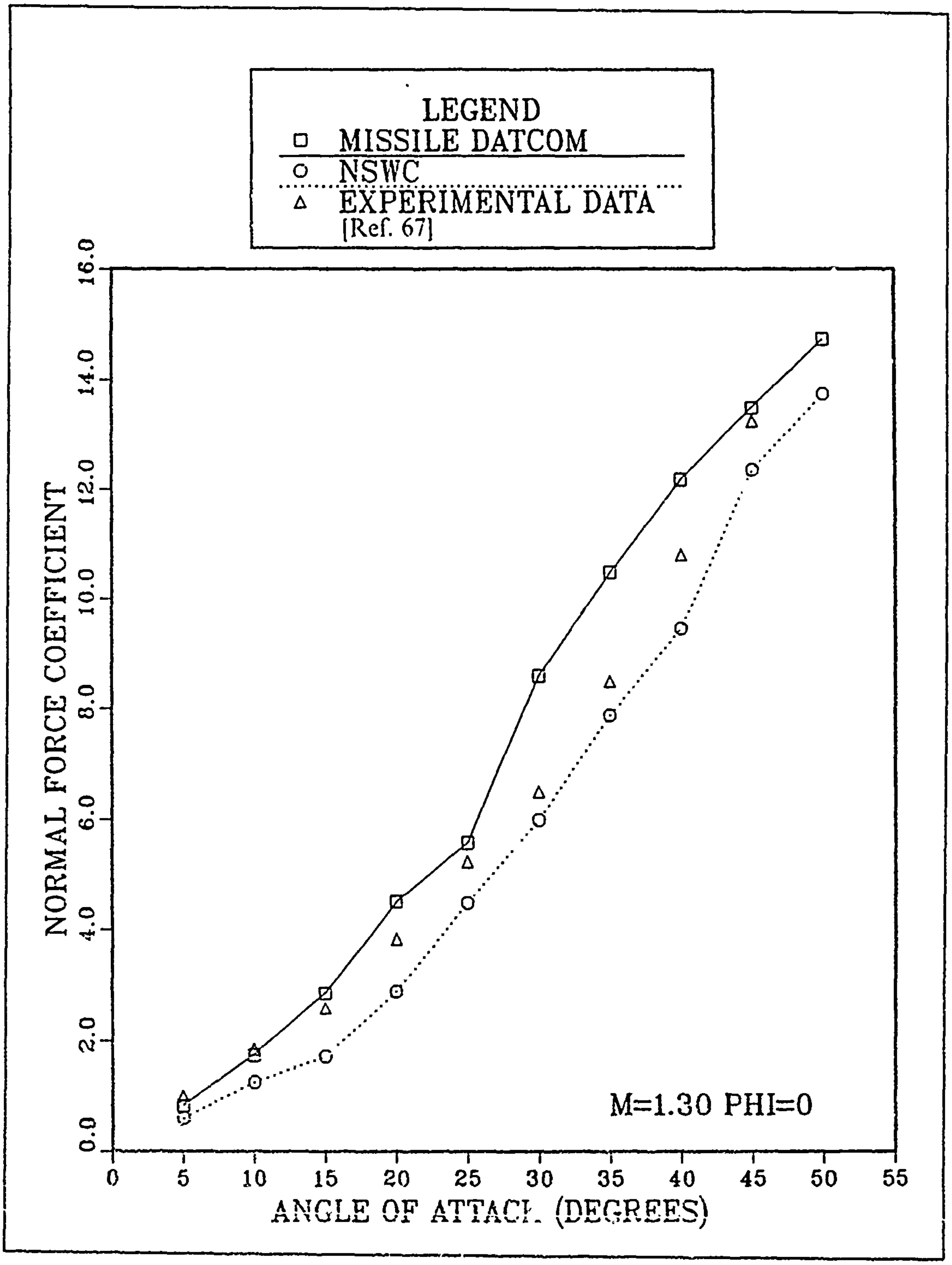

Figure 13. Normal Force Coefficient Comparison for the Air Slew Demonstrator

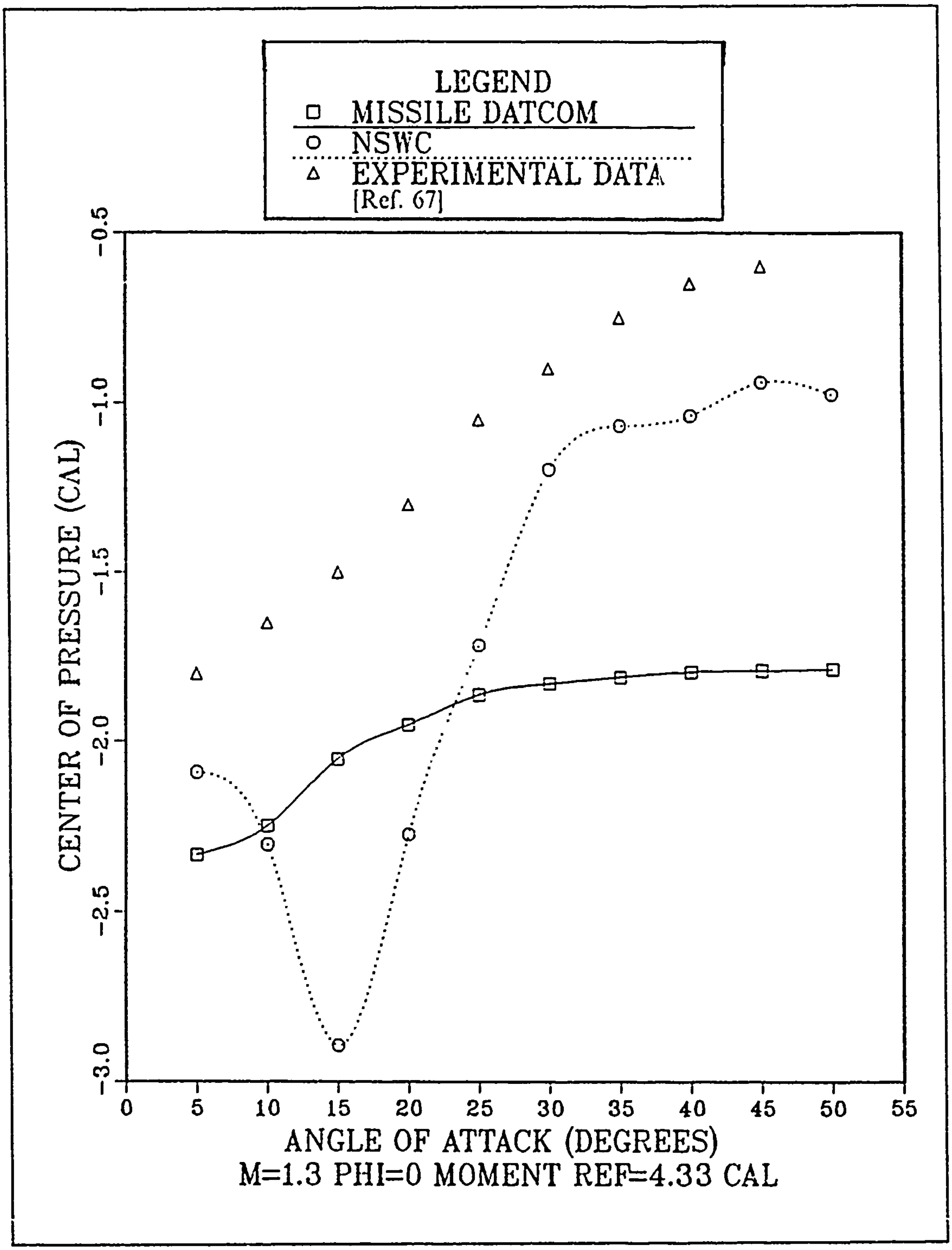

Figure 14. Center of Pressure Comparison for the Air Slew Demonstrator

gles of attack. A rough equivalence exists between the two programs for prediction at angle of attack less than 40 degrees.

D. TMX-2774 (T-9 TAIL)

The TMX-2774 geometry is presented in Figure 16 on page 51. Comparison testing was conducted at zero degree angle of attack, with no control deflection and no roll angle. Mach conditions were incremented from low supersonic to high supersonic. The experimental data in Figure 17 and Figure 18 are from Nichols [Ref. 69].

1. Normal Force Coefficient Derivative

Normal force curve slope predictions for the TMX-2774 appear in Figure 17. The NSWC curve shows slight underprediction for the low supersonic region and a slight overprediction for higher Mach numbers. The MISSILE DATCOM curve maintains an overprediction for all Mach numbers, although the low supersonic Mach estimates are a much closer fit to the experimental data. The overall accuracy of the NSWC code is good, while the MISSILE DATCOM program can be considered less correct at high Mach numbers.

2. Center of Pressure

The center of pressure predictions are plotted with the experimental data in Figure 18 on page 53. The data are taken as ratios to the body length, and referenced 6.81 calibers from the nose. The NSWC prediction curve is of excellent accuracy with respect to the experimental data. The MISSILE DATCOM estimates are of the right functional form, but are underpredicted for all Mach conditions.

E. TMX-1751

The TMX-1751 is a wing-body-tail configuration, as is shown in Figure 19 on page 54. The comparison runs were conducted within the supersonic Mach region at zero degree angle of attack. Control deflections and roll angles were not considered. Experimental data for Figure 20 through Figure 22 are from Ref. 69.

1. Normal Force Coefficient Derivative

The normal force curve slopes are presented in Figure 20 on page 55. The NSWC and MISSILE DATCOM values show good correlation to the experimental data, particularly between Mach 2.5 and Mach 4.5. The NSWC program provides a high level of accuracy within this Mach range; however, a small degree of overprediction is apparent. The MISSILE DATCOM prediction curve is also accurate within this Mach range, although the amount of overprediction is noticeably greater than for the NSWC program.

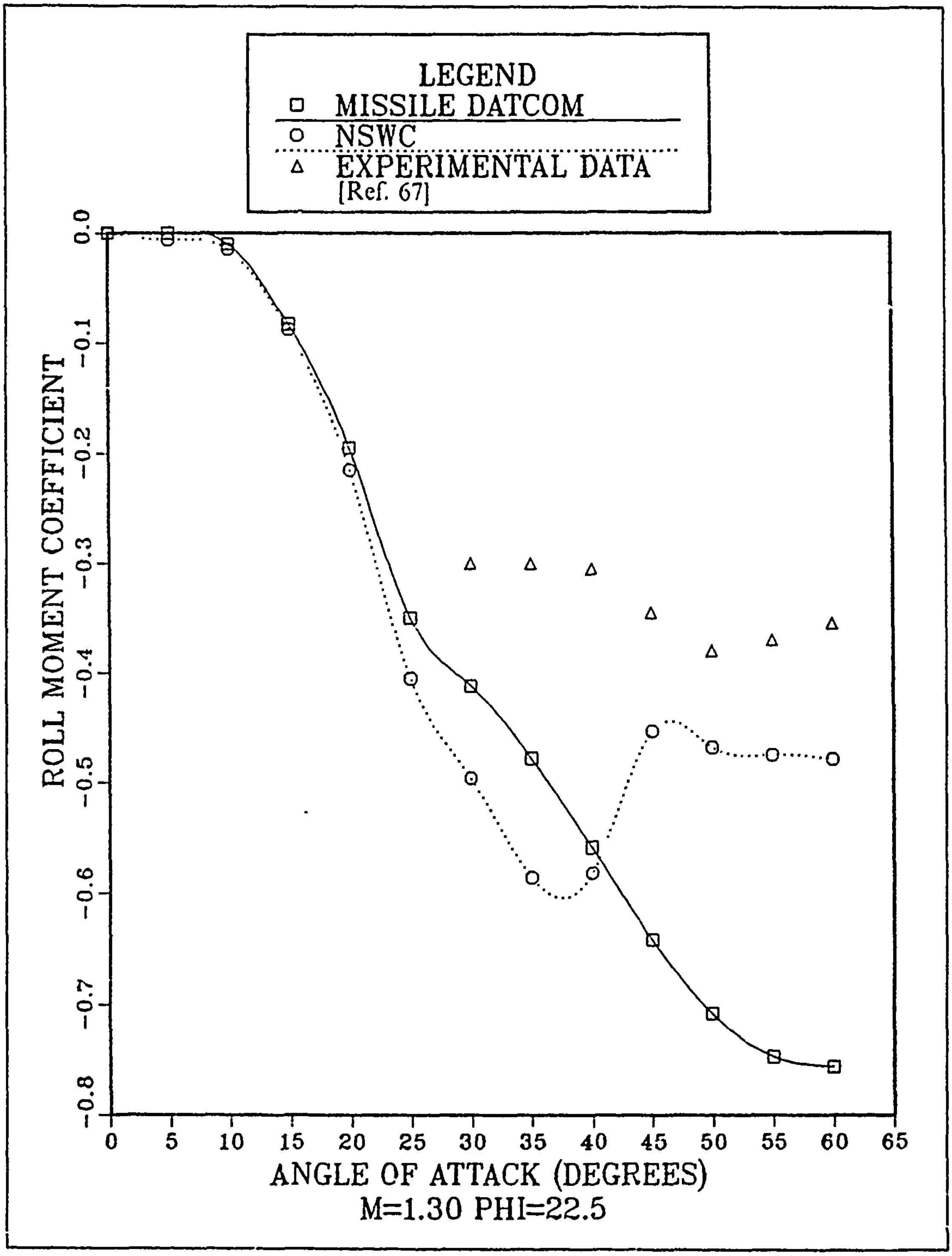

Figure 15. Roll Moment Comparison for the Air Slew Demonstrator

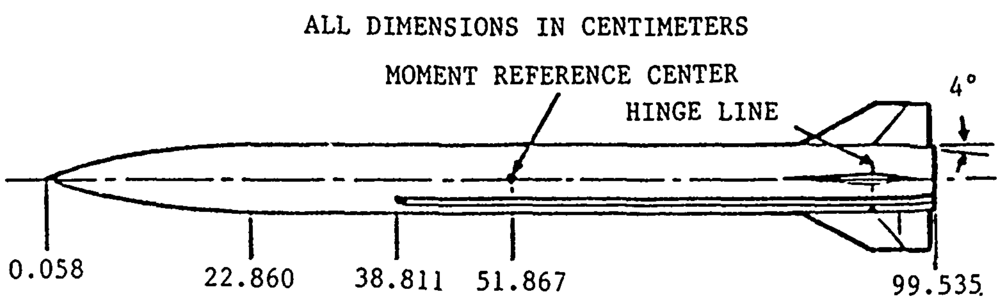

Figure 16. TMX-2774 (T-9 Tail) [Ref. 54, p. 42]

2. Center of Pressure

The predictions of center of pressure coefficients are presented in Figure 21 on page 56. The output values are expressed as ratio to the body length, referenced 8.41 calibers from the nose tip. The MISSILE DATCOM and NSWC plots are nearly identical in form, with both programs underpredicting the experimental data. While the MISSILE DATCOM and NSWC programs fail to replicate the functional form of the experimental data, the prediction values are of the correct order of magnitude, such that the relative errors are reasonably small. In comparison to the trend of the experimental data, the linear form of the NSWC and MISSILE DATCOM curves suggest that the low supersonic prediction accuracy would be increasingly poor.

3. Drag Coefficient

The zero degree angle of attack drag coefficient data are shown in Figure 22 on page 57. Both the NSWC and MISSILE DATCOM programs overpredict drag coefficient values in comparison to the experimental data. although the functional form of the prediction curves is basically correct. The degree of error is greater than in the

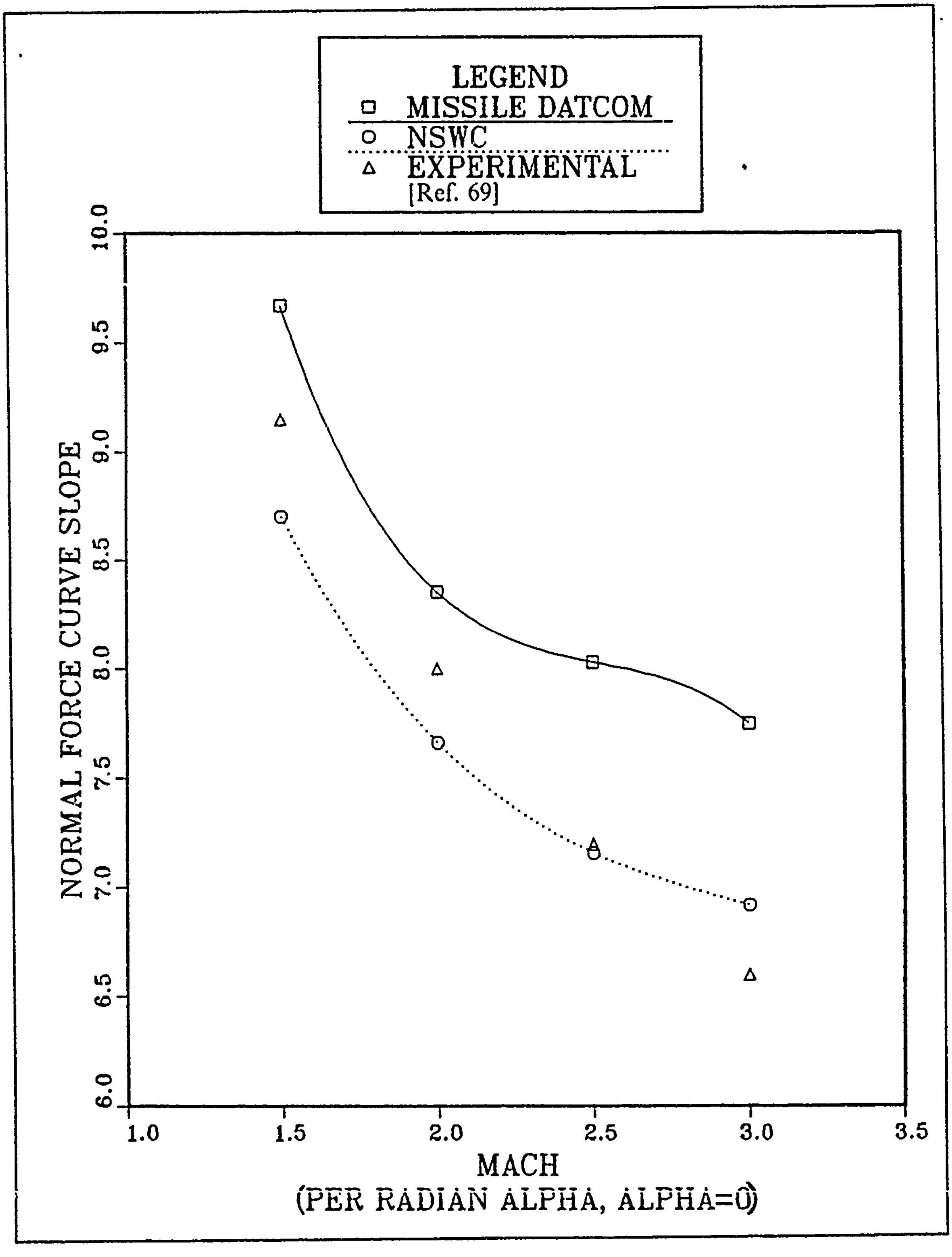

Figure 17. Normal Force Curve Slope Comparison for the TMX-2774 (T-9 Tail)

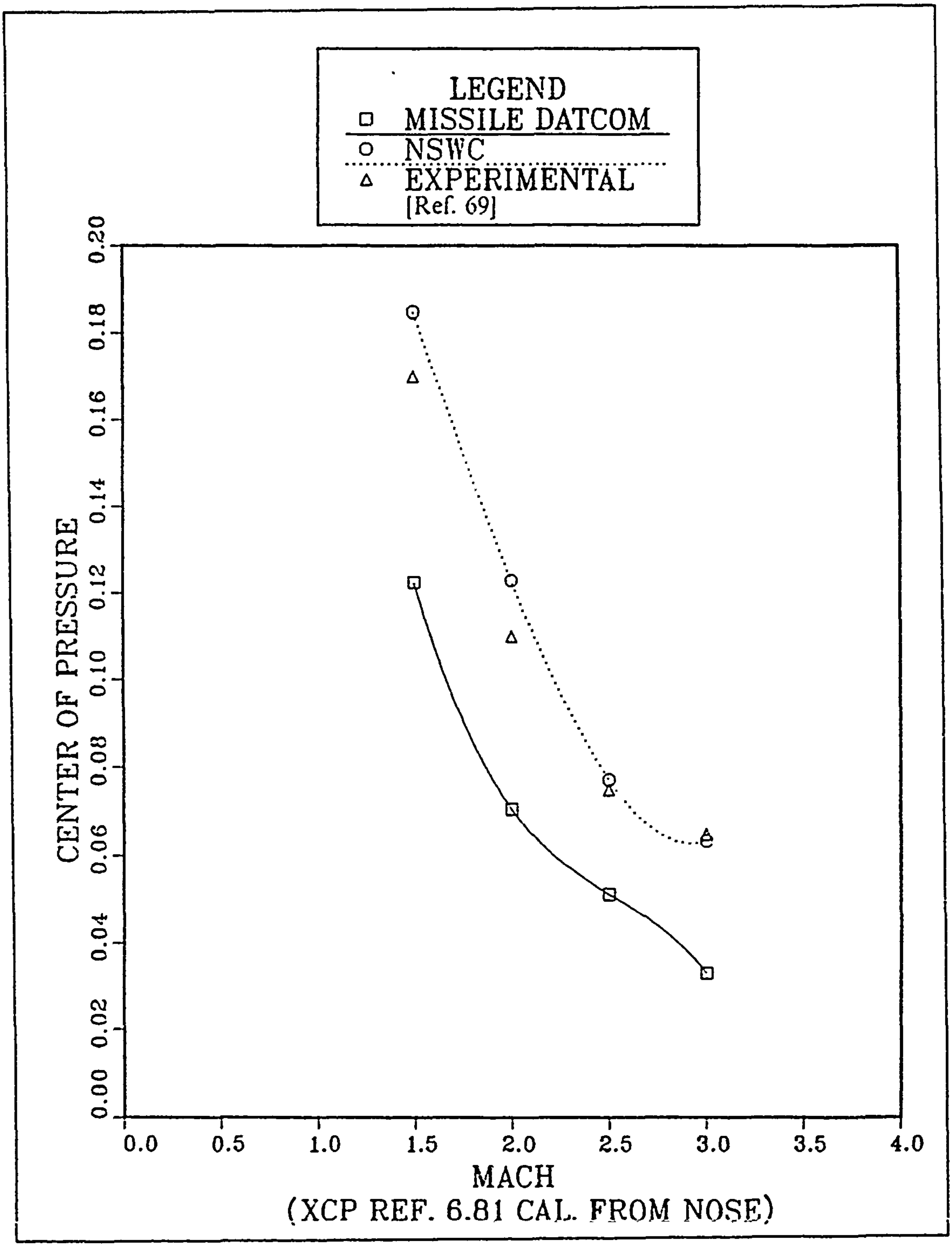

Figure 18. Center of Pressure Comparison for the TMX-2774 (T-9 Tail)

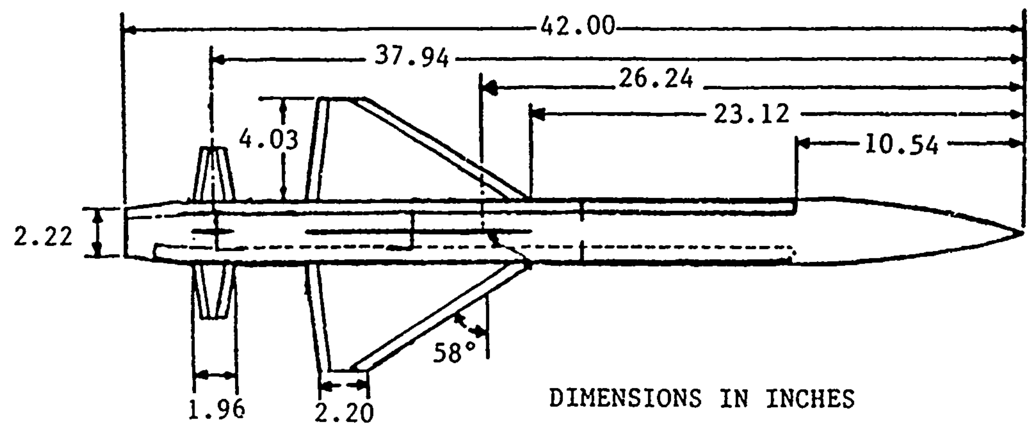

Figure 19. TMX-1751 [Ref. 54, p. 67]

body-tail Basic Finner comparison, with the trend to overpredict the drag coefficents rather than the underprediction seen for the Basic Finner.

F. STANDARD MISSILE MODEL

The Standard Missile model configuration is presented in Figure 23 on page 58. This scale model is similar in design to the Navy Standard Missile, and is used in support of aerodynamic research at the Naval Postgraduate School. Previous work by Rabang included high angle of attack wind tunnel testing of this model in wing-body-tail and body-tail configurations, the empirical data of this testing are used as the reference data in the following comparisons [Ref. 70].

Comparison runs were made at a low subsonic Mach number of 0.10 and a Reynolds number of 1.1E5. Angle of attack was incremented from 0 to 90 degrees. These conditions prevented use of the NSWC code, which is restricted to transonic and supersonic Mach for high angle of attack analysis, as shown in Figure 1 on page 24. Body-wing-tail and body-tail configurations were input with no roll angle; the body-wing-tail configuration was additionally run with a 45 degree roll angle input.

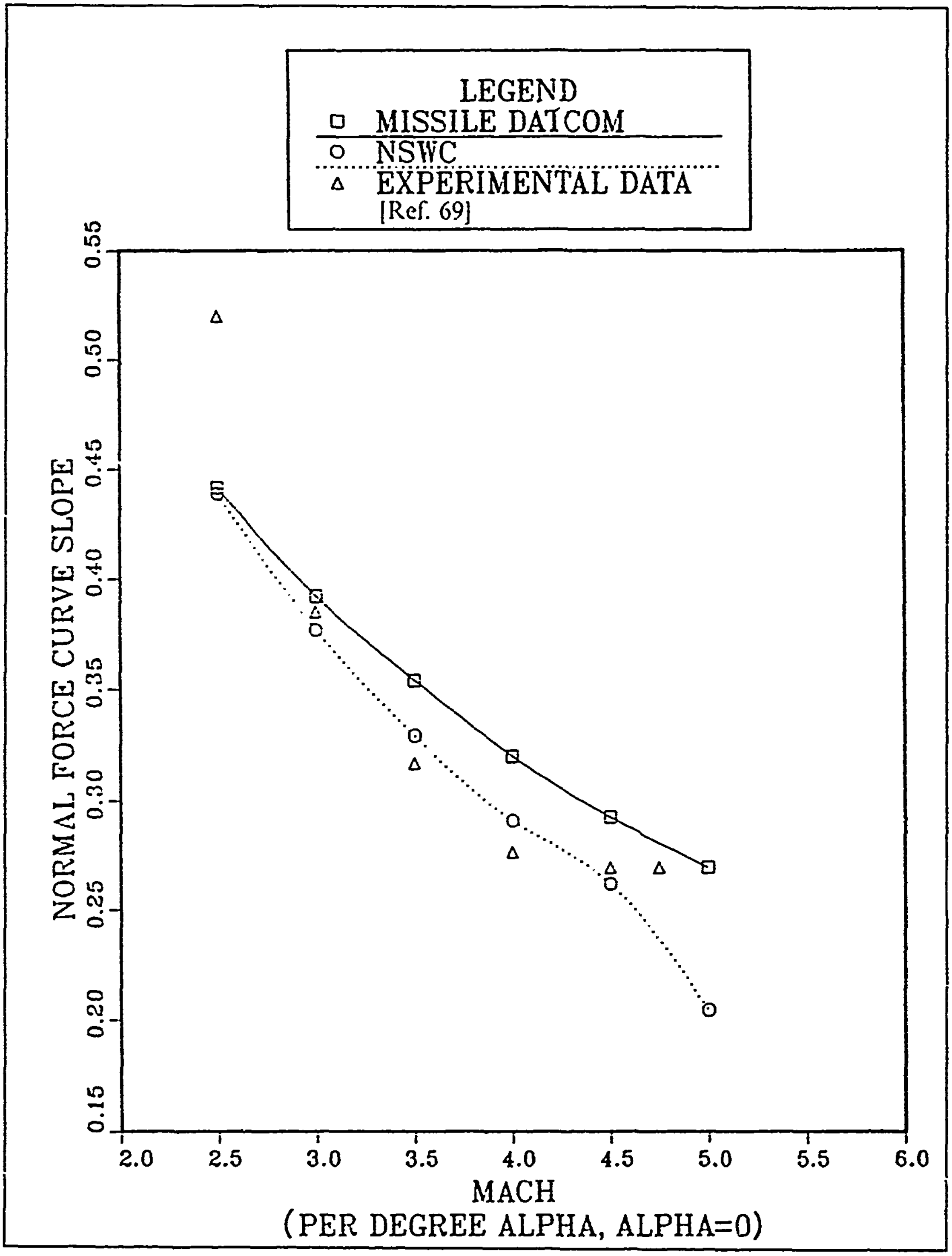

Figure 20. Normal Force Curve Slope Comparison for the TMX-1751

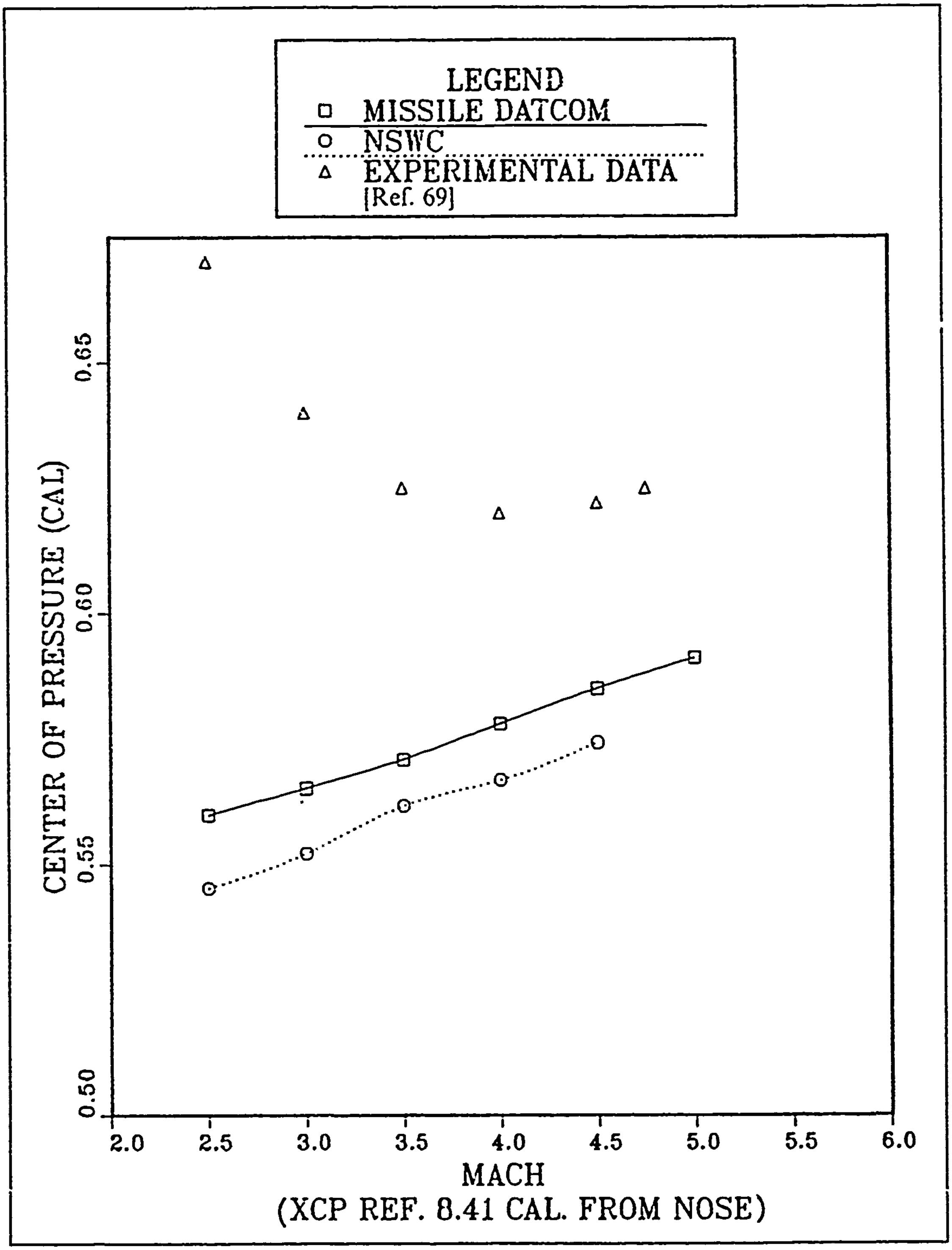

Figure 21. Center of Pressure Comparison for the TMX-1751

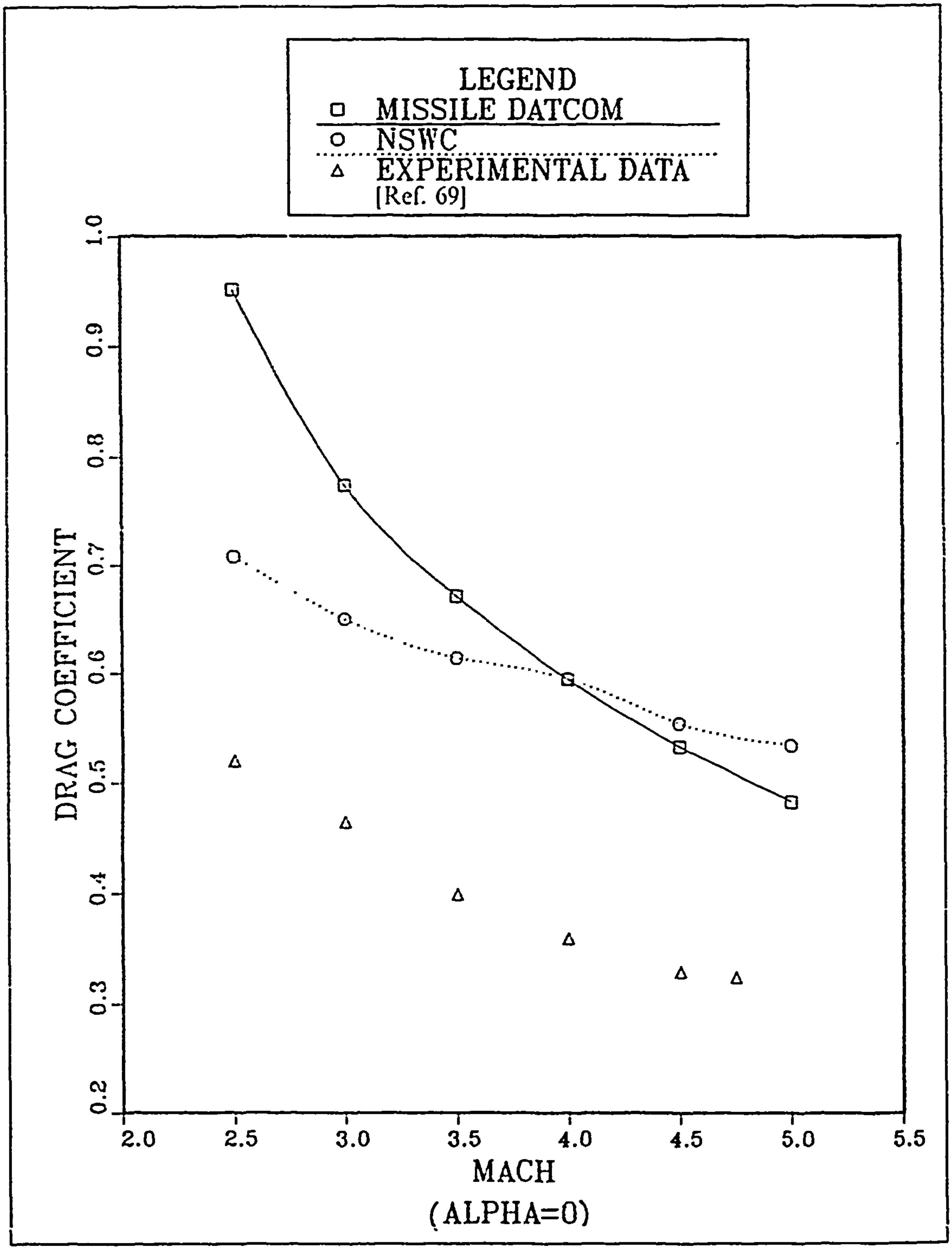

Figure 22. Drag Coefficient Comparison for the TMX-1751

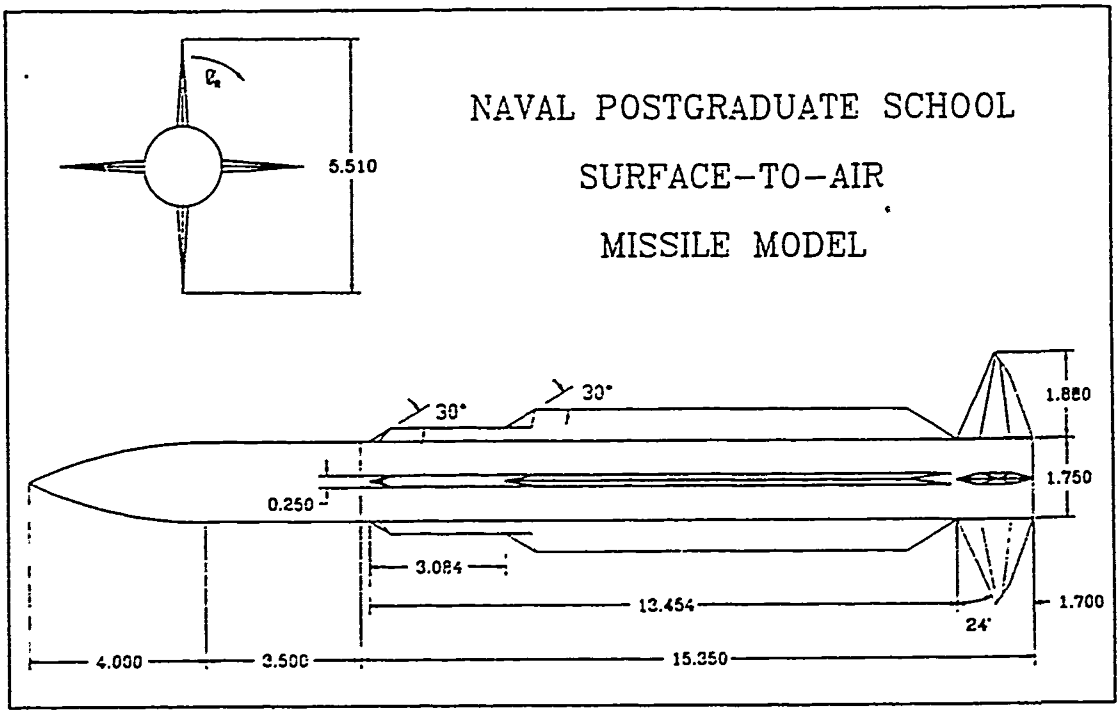

Figure 23. Standard Missile Model (Dimensions in Inches)

Geometry inputs for the body-tail configuration case were rather direct; however, the description of the wing geometry was more difficult due to the non-traditional shape An approximate fin description was input which ignored the break in the wing leading edge. This was done by defining the tip chord dimension at the tip span station such that a continuous leading edge is taken from the leading station of the root chord at a sweep angle of 30 degrees.

1. Normal Force Coefficient for the Body-Tail Configuration

The MISSILE DATCOM prediction is quite good, as can be seen in Figure 24 on page 59. The normal force coefficient is very accurately described up to 50 degrees, at which point an underprediction trend commences. As the slope of the experimental data curve begins to rapidly diminish, near 65 degrees, the MISSILE DATCOM curve maintains a strong positive slope. The high angle of attack portion of the MISSILE DATCOM curve appears functionally correct, but somewhat unresponsive to the non-linear effects reflected in the wind tunnel data for angles of attack greater than 50 degrees. This angle of incidence corresponds to the observed onset of unsteady, asymmetric separation.

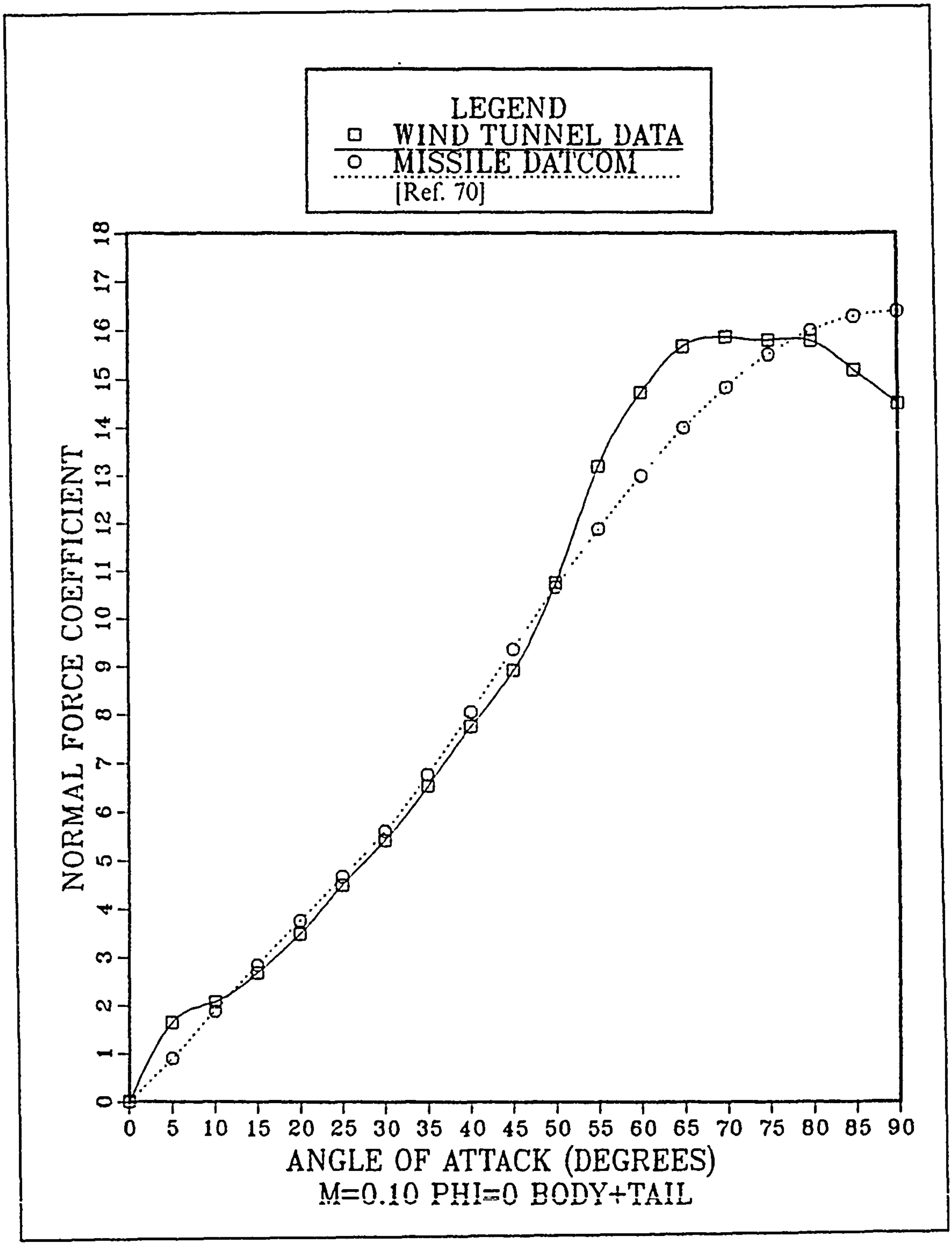

Figure 24. Normal Force Comparison for the Standard Missile Model

2. Normal Force Coefficient for the Body-Wing-Tail Configuration

As can be seen from the data curves in Figure 25 on page 61, the MISSILE DATCOM estimates of normal force coefficient are underpredicted for the more complex body-wing-tail configuration. The prediction error is maximum between 15 and 65 degrees, which is a known range of deviation for the Allen and Perkins plus Jorgensen crossflow method, as was previously mentioned for the Air Slew Demonstrator. This angle of attack range is roughly equivalent to the incidence envelope in which nonlinear aerodynamic effects are most pronounced. It is unclear what effect the approximate wing description contributed to the relative prediction error, although it can be seen that the inclusion of wing effects dramatically shifts the onset of nonlinear lift to lower angles of attack.

3. Normal Force Coefficient for the Body-Wing-Tail Configuration

The normal force curves shown in Figure 26 on page 62 indicate a nearly constant underprediction for the Standard Missile model at a 45 degree roll angle. MISSILE DATCOM accuracy is fairly good up to 70 degrees, above which the prediction curve continues at a positive slope without the inflection and down turn present in the wind tunnel data.

G. SUMMARY OF RESULTS

The comparison runs between the NSWC and MISSILE DATCOM aeroprediction codes indicate that both programs are suitable for preliminary design applications in which an accurate prediction of the trend in aerodynamic coefficients (at the correct order of magnitude) is of greater importance than the precision of specific prediction values. The following sections generalize the prediction performance of each code, based on an examination of the output from the preceeding comparison trials.

1. MISSILE DATCOM

The MISSILE DATCOM prediction of normal force coefficients is considered reasonably accurate for both low and high angle of attack conditions. The best prediction was output for the Basic Finner model in Figure 8 on page 40, although the normal force estimates for the Air Slew Demonstrator, TMX-1751 and Standard Missile model are nearly as accurate. The normal force coefficients for high angle of attack conditions are seen to be slightly overpredicted for the Air Slew Demonstrator and Standard Missile model (body-tail) configuration. A significant underprediction is present for the body-wing-tail Standard Missile model at angles of attack normally associated with nonlinear aerodynamics.

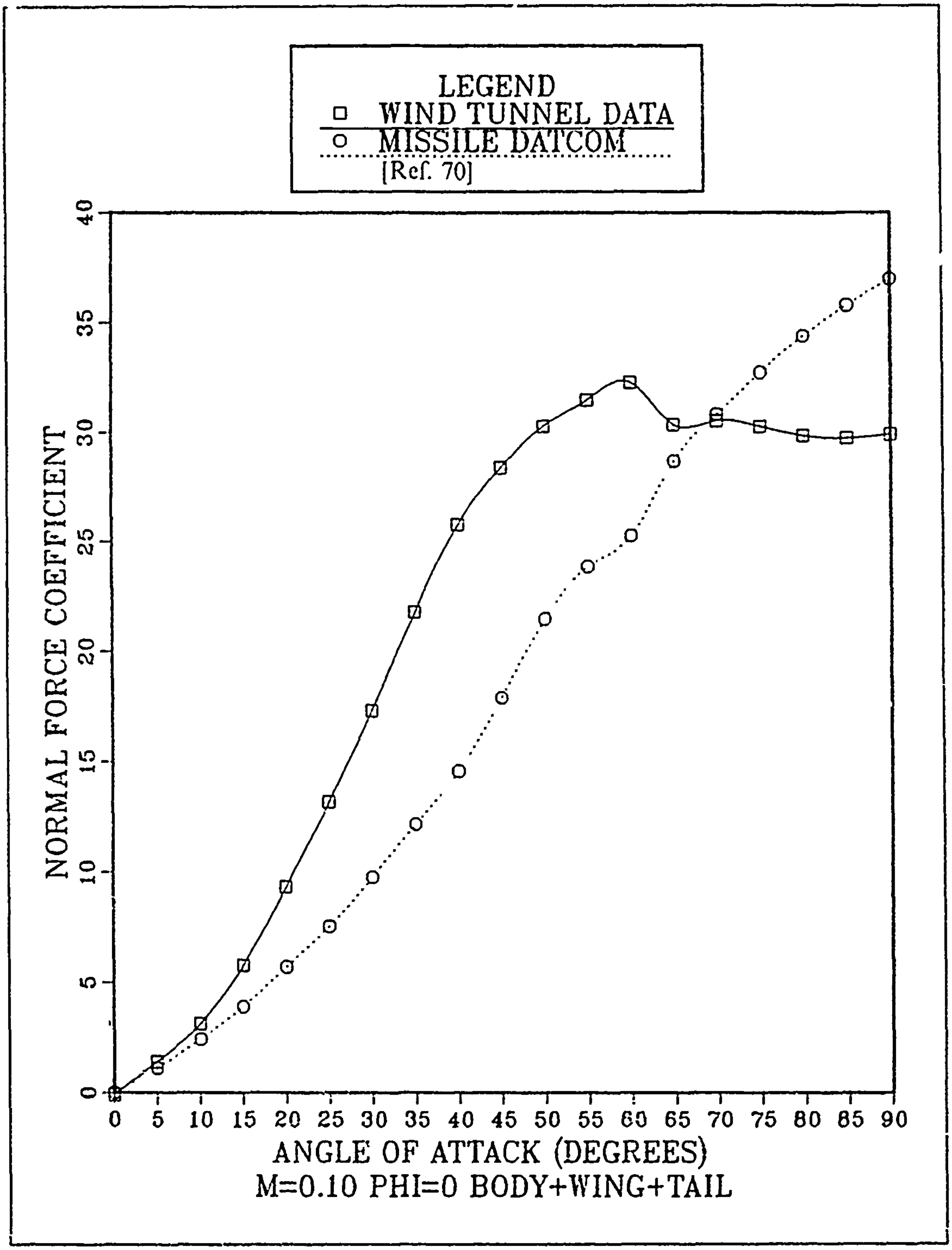

Figure 25. Normal Force Comparison for the Standard Missile Model

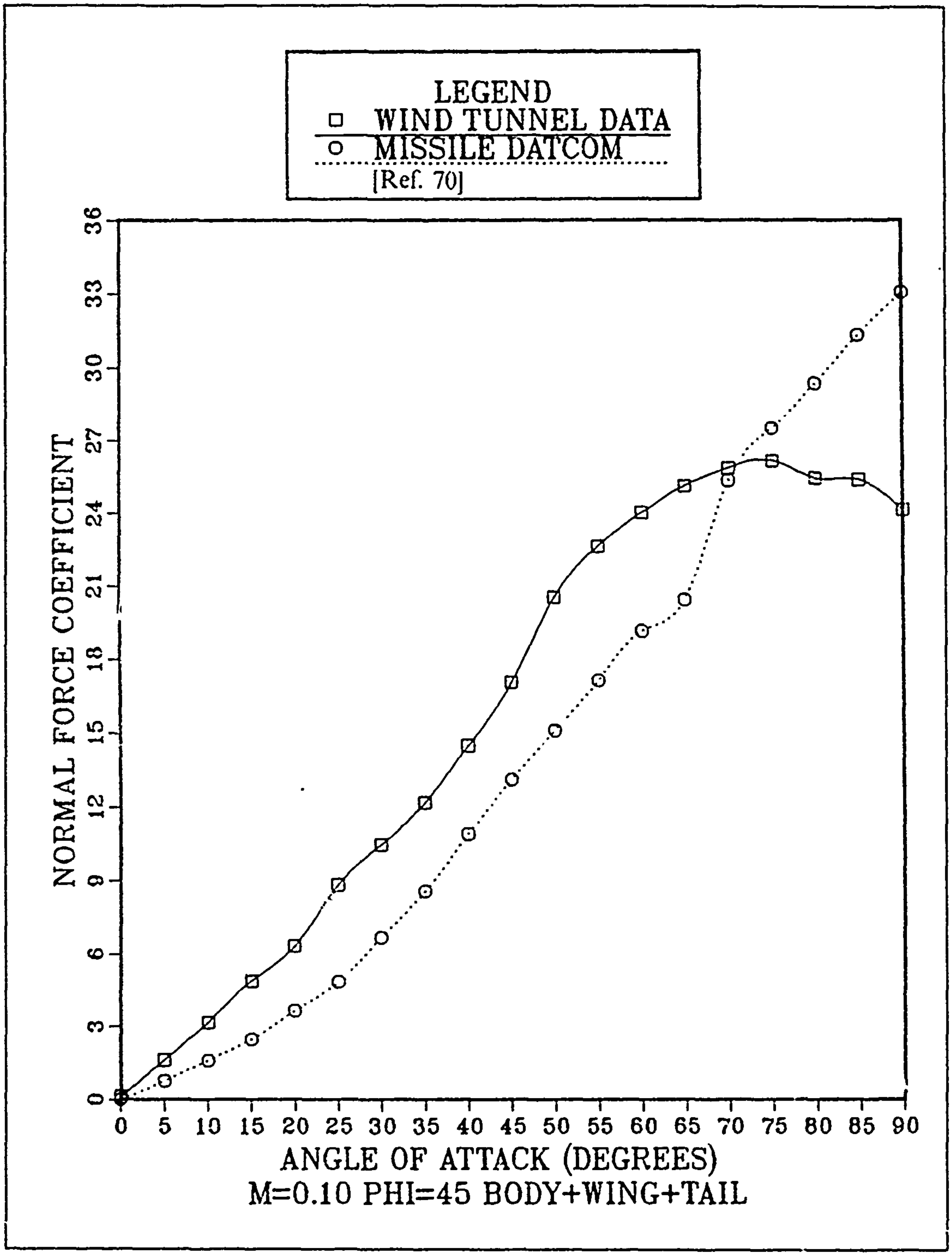

Figure 26. Normal Force Comparison for the Standard Missile Model

Center of pressure predictions are accurate to within 10 percent of the experimental data for the TMX-2774 and Basic Finner, while the Army-Navy Spinner and Air Slew Demonstrator estimates show prediction errors of up to 100 percent. An underprediction error is characteristic, particularly for high supersonic Mach numbers. The estimates of axial position are, however, generally of the correct order of magnitude, and typically reflect the functional form of the experimental data. The most accurate prediction of center of pressure was for the Basic Finner, while the high angle of attack predictions for the Air Slew Demonstrator show significant error.

The most accurate drag coefficient predictions are within a few percent of the experimental data, while the less correct values reflect an 85 percent error. Accuracy is diminished within the transonic and supersonic regions. Above Mach 2.5, the drag coefficient estimates are seen to converge on the experimental data. The quality of the drag coefficient predictions is seen to decrease as the configuration geometry becomes more complex. The Army-Navy Spinner comparison of Figure 5 on page 35 shows a good level of accuracy with the experimental data. Drag coefficient estimates for the cone-cylinder-tail configuration of the Basic Finner are much less accurate, but still provide a loose correlation to the empirical values, as shown in Figure 10 on page 43. The body-wing-tail geometry of the TMX-1751 results in still further reduction in the accuracy of the drag coefficient predictions, with the low supersonic portion of the output divergent from the experimental data.

An evaluation as to the performance of dynamic derivative prediction is not possible. The pitch damping coefficient data in Figure 6 on page 37 and Figure 11 on page 44 show excessive underprediction of the experimental data, although a trend similar to the NSWC curve and the reference data is displayed. As there is some degree of ambiguity surrounding the MISSILE DATCOM dynamic derivative output, and no test case or experimental data which can be used for source code verification or comparison, it must suffice to report that the program currently provides no reliable prediction of pitch damping coefficients. It is believed, however, that the computational methods are theoretically sound, and that the error is connected to the reference definition of the output quantities.

2. NSWC

Normal force coefficient prediction is considered very accurate. Prediction values are within 10 percent of the experimental data, and consistently replicate the functional form of the empirical results. Some underprediction is present in the normal force coefficient estimates of each configuration trial; however, the degree of error is characteristically small. No significant degradation in the quality of prediction is seen to result from model complexity or angle of attack; a modest increase in prediction error occurs for transonic Mach numbers in the Basic Finner output of Figure 8 on page 40, as well as for the Army-Navy Spinner of Figure 3 on page 32. The high angle of attack predictions for the Air Slew Demonstrator are exceptionally accurate.

Center of pressure is predicted with less accuracy than the normal force coefficient. While the Basic Finner and TMX-2774 comparisons fit reasonably well with the experimental data, the Air Slew Demonstrator and TMX-1751 predictions are accurate only in magnitude. Center of pressure coefficients are generally underpredicted. The accuracy of prediction at angle of attack is marginal, as indicated by the Air Slew Demonstrator; Figure 14 on page 48 projects a confusing movement for the center of pressure at angles of attack between 5 and 30 degrees which can not be adequately explained.

Drag coefficient predictions do not consistently replicate the experimental data. The prediction error is seen to vary from just a few percent for the Army-Navy Spinner projectile, to roughly 80 percent for the TMX-1751. The accuracy is seen to diminish as the configuration geometry of the model becomes more complex. While accuracy is excellent for the Army-Navy Spinner projectile, an underprediction error is evident for the body-tail Basic Finner; overprediction of drag coefficients results for the body-wing- tail TMX-1751. In all cases, however, the functional form of the drag coefficient prediction curves is in close agreement with the experimental data.

Pitch damping coefficient estimates are satisfactory, although only two configuration cases were examined. The coefficient values are typically overpredicted for all Mach regions, although the trend of the prediction curve is quite similar to the experimental data. The pitch damping coefficient predictions for the Basic Finner are within 15 percent of the experimental data; a 40 percent error is present for the high Mach predictions of the Army-Navy Spinner. Subsonic and transonic predictions are more accurate than those for the supersonic Mach region. The predicted values for the Basic Finner are in very close agreement with the experimental data; the overprediction trend at high Mach numbers for the Army-Navy Spinner may well be the result of the comparative value selection process of the LMSC and SPINNER routines.

V. CONCLUSIONS

The usefulness or worth of aeroprediction codes can be measured in various ways. The design engineer or project manager is most likely concerned with the veracity and flexibility of the program; that is, whether or not the predicted values will accurately replicate certain experimental data, and therefore at least reduce the amount of costly preliminary testing and experimentation. Exact precision is not always required so long as the trend and character of the computer solutions are repetitive and thoroughly documented for various missile configurations and flight conditions. The NSWC and MISSILE DATCOM aeroprediction codes have demonstrated a generally comparable performance in the prediction of various aerodynamic coefficients. As the prediction curves are seen to generally replicate the trend of the experimental data at the correct order of magnitude, the NSWC and MISSILE DATCOM codes are found to possess the accuracy required to conduct preliminary design and aerodynamic analysis. Introductory level research of conventional or arbitrary missile configurations across a wide range of input conditions is an ideal application for the MISSILE DATCOM prediction program. The NSWC aeroprediction code is better suited for a more detailed aerodynamic investigation of specific missile geometries in support of feasibility studies or intermediate research.

An analysis of asymmetric vortex separation is currently not feasible for smaller research or academic institutions. The study of nonlinear and time variant flow mechanisms has traditionally made use of complex and expensive numerical techniques which cannot be operated efficiently by the majority of mainframe computer systems. The requirement for a low-level, preliminary design code capable of conducting asymmetric analysis is evident, and underscores the need to continue development of such programs. The VORSTAB II computer program may well represent a first step in fulfilling this need. The capabilities and prediction performance of the VORSTAB II source code should be investigated as this program becomes available to a larger user base.

APPENDIX A. BASIC FINNER PITCH DAMPING COEFFICENT PREDICTION

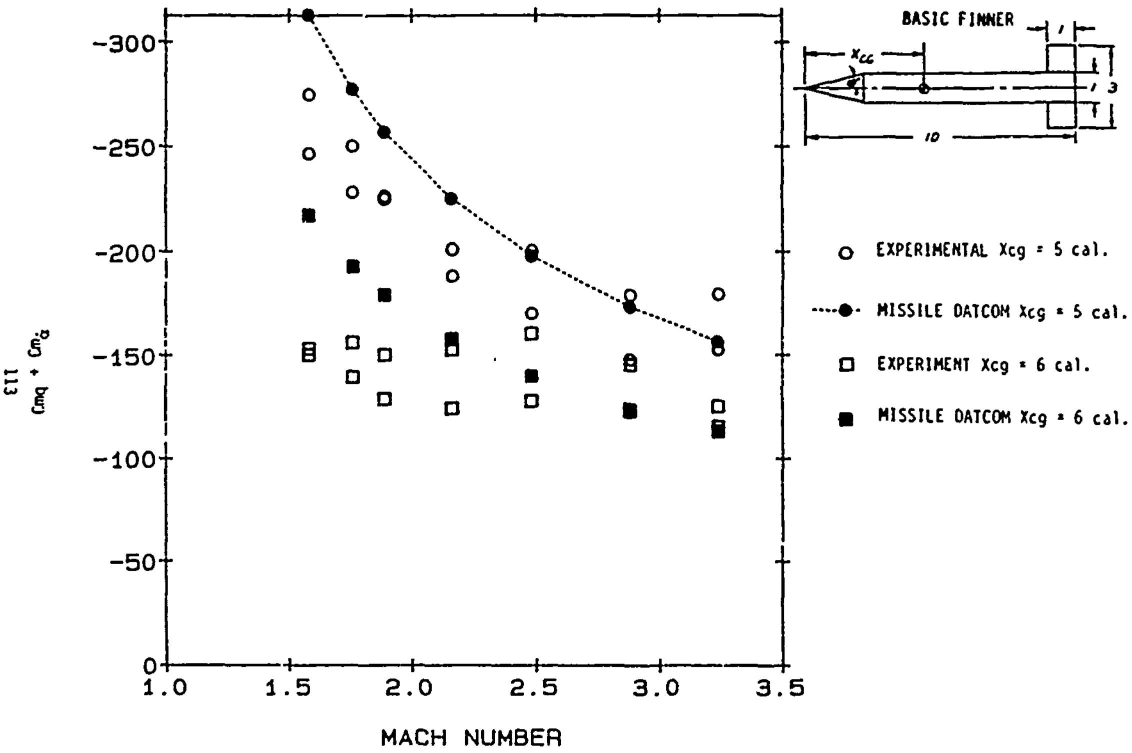

FIGURE 63 CONE-CYLINDER TAIL PITCH DAMPING COMPARISON

Source: [Ref. 26. p. 113]

APPENDIX B. DYNAMIC DERIVATIVE OUTPUT OF PITCH DAMPING COEFFICIENT

THE USAF AUTOMATED MISSILE DATCOM • REV 11/85 •
AERODYNAMIC METHODS FOR MISSILE CONFIGURATIONS
EXAMPLE PROBLEM - PLANAR WING PLUS TAIL CONFIGURATION
STATIC AERODYNAMICS FOR BODY-FIN SET 1 AND 2

CASE 1
PAGE 20

FLIGHT CONDITIONS								REFERENCE DIMENSIONS				
MACH NUMBER	ALTITUDE FT	VELOCITY FT/SEC	PRESSURE LB/IN**2	TEMPERATURE DEG R	REYNOLDS NUMBER 1/FT	SIDESLIP ANGLE DEG	ROLL ANGLE DEG	REF. AREA IN**2	REF. LENGTH LONG. IN	REF. LENGTH LAT. IN	MOMENT REF. CENTER LONG. IN	MOMENT REF. CENTER VERTICAL IN
2.36					3.000E+06	0.00	0.00	11.045	3.750	3.750	10.750	0.000

ALPHA	LONGITUDINAL CN	LONGITUDINAL CM	LONGITUDINAL CA	LATERAL DIRECTIONAL CY	LATERAL DIRECTIONAL CLN	LATERAL DIRECTIONAL CLL	DERIVATIVES (PER DEGREE) LONGITUDINAL CNA	LONGITUDINAL CMA	LATERAL DIRECTIONAL CYB	LATERAL DIRECTIONAL CLNB	LATERAL DIRECTIONAL CLLB
0.00	0.000	0.000	0.347	0.000	0.000	0.000	2.588E-01	-3.424E-01			
4.00	1.124	-1.472	0.368	0.000	0.000	0.000	3.034E-01	-3.934E-01			
8.00	2.428	-3.149	0.368	0.000	0.000	0.000	3.717E-01	-4.804E-01			
12.00	4.104	-5.327	0.368	0.000	0.000	0.000	4.317E-01	-5.783E-01			
16.00	5.882	-7.780	0.369	0.000	0.000	0.000	4.414E-01	-6.214E-01			
20.00	7.635	-10.298	0.370	0.000	0.000	0.000	4.194E-01	-6.175E-01			
24.00	9.239	-12.720	0.371	0.000	0.000	0.000	4.035E-01	-5.909E-01			
28.00	10.863	-15.026	0.372	0.000	0.000	0.000	4.005E-01	-5.624E-01			

ALPHA	CL	CD	CL/CD	X-C.P.
0.00	0.000	0.367	0.000	-1.323
4.00	1.098	0.445	2.462	-1.309
8.00	2.353	0.702	3.352	-1.297
12.00	3.937	1.213	3.245	-1.298
16.00	5.553	1.976	2.810	-1.323
20.00	7.048	2.959	2.382	-1.349
24.00	8.289	4.097	2.023	-1.377
28.00	9.418	5.429	1.735	-1.383

Sample of Test Case Header for Flight and Reference Conditions

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AERODYNAMIC METHODS FOR MISSILE CONFIGURATIONS
EXAMPLE PROBLEM - PLANAR WING PLUS TAIL CONFIGURATION
BODY + 2 FIN SETS DYNAMIC DERIVATIVES

CASE 1
PAGE 3

FLIGHT CONDITIONS								REFERENCE DIMENSIONS				
MACH NUMBER	ALTITUDE FT	VELOCITY FT/SEC	PRESSURE LB/IN**2	TEMPERATURE DEG R	REYNOLDS NUMBER 1/FT	SIDESLIP ANGLE DEG	ROLL ANGLE DEG	REF. AREA IN**2	REF. LENGTH LONG. IN	REF. LENGTH LAT IN	MOMENT REF CENTER LONG. IN	MOMENT REF CENTER VERTICAL IN
2.36					3.000E+06	0.00	0.00	11.045	3.750	3.750	10.750	0.000

ALPHA	DYNAMIC DERIVATIVES (PER DEGREE) CMQ	CMAD	CMQ+CMAD
0.0	5.584E-01	3.868E-01	-4.64110E+00
4.0	6.547E-01	4.465E-01	-5.33195E+00
8.0	8.022E-01	5.478E-01	-6.51844E+00
12.0	9.317E-01	6.353E-01	-7.83775E+00
16.0	9.877E-01	6.735E-01	-8.78341E+00

Dynamic Derivative Output Including Pitch Damping Coefficient

Source: [Ref. 35, p. 123]

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